RSC Advances



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REVIEW

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Cite this: RSC Adv., 2022, 12, 27746

A review on the characterization of metal active sites over Cu-based and Fe-based zeolites for NH₃-SCR

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Cu-based and Fe-based zeolites are promising catalysts for NH₃-SCR due to their high catalytic activity, wide temperature window and good hydrothermal stability, while the detailed investigation of NH3-SCR mechanism should be based on the accurate determination of active metal sites. This review systematically summarizes the qualitative and quantitative determination of metal active sites in Cubased or Fe-based zeolites for NH₃-SCR reactions based on advanced characterization methods such as UV-vis absorption (UV-vis), temperature-programmed reduction with H₂ (H₂-TPR), X-ray photoelectron spectroscopy (XPS), X-ray absorption fine structure spectroscopy (XAFS), Infrared spectroscopy (IR), Electron paramagnetic resonance (EPR), Mössbauer spectroscopy and DFT calculations. The application and limitations of different characterization methods are also discussed to provide insights for further study of the NH₃-SCR reaction mechanism over metal-based zeolites.

Received 15th August 2022 Accepted 20th September 2022

DOI: 10.1039/d2ra05107a

rsc li/rsc-advances

1 Introduction

 NH_3 -SCR technology, the selective catalytic reduction of NO_x (NO and NO₂) to N₂ and H₂O by NH₃ with the aid of catalyst and oxygen, has become one of the main industrial deNO_x technologies due to its high efficiency and low cost.¹⁻⁴ The WO₃-V₂O₅/TiO₂ catalyst is the first commercialized NH₃-SCR catalyst since the 1970s.⁵ However, WO₃-V₂O₅/TiO₂ catalysts are gradually abandoned in many countries due to their narrow temperature window (320-450 °C), poor hydrothermal stability in NH₃-SCR, and more specifically, their high biological toxicity due to the need for vanadium species.6-8

Cu-based and Fe-based zeolites are two potential NH₃-SCR catalysts with high catalytic activity, wide temperature window and good hydrothermal stability.8-11 By delicately adjusting the content and distribution of metal species,^{12,13} and by delicately selecting the type of support zeolites,^{10,14} a variety of highly efficient Cu or Fe-based NH3-SCR zeolite catalysts have been developed, such as Fe/SSZ-13, Fe/Beta, Fe/ZSM-5, Cu/SSZ-13, Cu/SAPO-34, and Cu/LTA zeolites.15,16 Especially, small-pore Cu/SSZ-13 has been successfully applied in exhaust removal for diesel vehicles, though it still suffers from poor hydrothermal stability and poor sulfur resistance.16,17

Generally, the excellent redox properties and strong acidity are two crucial factors deciding the catalytic performance of a catalyst in NH₃-SCR.^{15,16,18,19} The acid sites in catalysts facilitate the adsorption and activation of NH₃ molecules, while the redox ability of catalysts originating from metal species mainly catalyze the redox cycle in NH3-SCR.² According to previous researches,13,20-24 various Fe or Cu species existed in Fe-based or Cu-based zeolites due to the similar formation energy of metal species or the easy interconversion of different metal species under SCR reaction conditions. Therefore, it is important to reveal the catalytic roles of different active metal species in zeolites, so as to clarify the reaction mechanism of NH₃-SCR over metal-based zeolites.

According to Gao et al.,13 there were mainly four kinds of iron species on Fe/SSZ-13 zeolites: isolated Fe²⁺ species, isolated Fe³⁺ species, dinuclear Fe³⁺ species ([HO-Fe-O-Fe-OH]²⁺), and multinuclear Fe_xO_y species which consist of trinuclear and highly aggregated Fe_xO_v species or nanoparticles. Based on detailed investigation on Fe/SSZ-13 zeolites, Gao et al.13,24 found that isolated Fe³⁺ species and dinuclear [HO-Fe-O-Fe-OH]²⁺ species were the dominant active sites at low-temperature (<300 $^{\circ}$ C) and high-temperature (\geq 300 $^{\circ}$ C) ranges for standard NH₃-SCR, respectively, though the [HO-Fe-O-Fe-OH]²⁺ species could also catalyze the undesirable ammonia oxidation side reaction. Besides, isolated Fe²⁺ species had almost no NH₃-SCR activity because of their low redox ability. In addition, the highly aggregated Fe_rO_v species in Fe/SSZ-13 zeolites, which catalyzed the ammonia oxidation side reactions, showed limited NH₃-

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Review

SCR activity even at high temperatures. As a summary, isolated Fe^{3+} and dinuclear $[HO-Fe-O-Fe-OH]^{2+}$ possess excellent catalytic activity in NH_3 -SCR, while isolated Fe^{2+} species, and highly aggregated Fe_xO_y species are undesirable for NH_3 -SCR.^{13,24}

Similar to Fe-based zeolites, several types of Cu species such as isolated Cu⁺ species, isolated Cu²⁺ species (including Cu²⁺– 2Z and [Cu(OH)]⁺–Z species, where Z represents zeolite), Cu²⁺ dimer species (including single O-bridged dicopper [Cu–O– Cu]²⁺, double O-bridged dicopper or even bis(μ -hydroxo)dicopper species), and multinuclear CuO_x species or highly aggregated CuO_x nanoparticles, can also be observed in Cubased zeolites, according to previous researches.^{4,12,25–28}

In general, researchers believed that isolated Cu^{2+} species were the main active sites for NH₃-SCR reactions over Cu-based zeolites.^{12,20,25,26} Xue *et al.*²⁹ had observed a positive correlation between the concentration of isolated Cu^{2+} species in Cu/SAPO-34 and the NO_x conversion, and further proved that the turnover frequency (TOF) of isolated Cu^{2+} species in Cu/SAPO-34 remained almost unchanged with Cu loadings at 100–200 °C in NH₃-SCR, which strongly proved that isolated Cu^{2+} species were the main active sites in NH₃-SCR. Moreover, Gao *et al.*²⁷ and Paolucci *et al.*³⁰ found that both Cu^{2+} –2Z and $[Cu(OH)]^+$ –Z species were the main active sites for standard NH₃-SCR reactions in Cu/SSZ-13, but Cu^{2+} –2Z species was more stable than $[Cu(OH)]^+$ –Z species, as the latter could be easily transformed into CuO_x species under hydrothermal aging conditions.

Furthermore, researchers found that dimeric Cu²⁺ species could also be the main active species for NH₃-SCR. Gao et al.¹² revealed that at low temperatures (<250 °C), the standard NH₃-SCR reaction rate was positively correlated with the square of Cu loadings over Cu/SSZ-13 zeolites, which confirmed the high NH₃-SCR activity of dimeric Cu²⁺ species in NH₃-SCR at low temperatures. However, the unstable dimeric Cu2+ species could be converted to isolated Cu²⁺ species at high temperatures, which became the main active sites for NH₃-SCR at high temperatures. Recently, many studies revealed that Cu⁺ species in Cu-based zeolites also played important roles in NH₃-SCR, especially at low temperatures.^{4,29,31,32} McEwen *et al.*²⁸ found that both Cu²⁺ and Cu⁺ species existed and participated in Cu/SSZ-13 zeolites during the NH₃-SCR reactions based on in situ X-ray absorption near edge spectra (XANES). Zhao et al.33 also found that the active species of NH₃-SCR over Cu-Mn/SAPO-34 zeolites were a mixture of Cu⁺ and Cu²⁺ species. Chen et al.³¹ revealed that the formation of highly stable Cu⁺ species in Cu/SSZ-13 was favorable for low-temperature (<200 °C) NH₃-SCR reactions.

In conclusion, different kinds of metal species had different redox ability, stability and coordination interactions with zeolite framework, which made them function differently in catalyzing NH₃-SCR reactions. However, the coexistence of various Fe species over Fe-based zeolites (or various Cu species over Cu-based zeolites) made the investigation of NH₃-SCR reactions mechanism difficult.¹² In order to suppress the occurrence of side reactions so as to investigate the detailed reaction pathway of NH₃-SCR, the total metal loadings in Cubased or Fe-based zeolites are usually lower than 5 wt%, normally at about 2 wt%, to suppress the formation of undesired highly aggregated metal oxides or nanoparticles.^{13,34,35} This poses a problem that, the qualitative and quantitative determination of various metal species over zeolites became difficult due to their low content and high dispersion over zeolites. Therefore, the detailed study on the type, content and distribution of active metal species in metal-based zeolites and their catalytic roles in NH₃-SCR with advanced characterization methods are necessary for a better understanding of NH₃-SCR reaction mechanism.

In the past 3 years, the studies of NH₃-SCR over metal oxides or metal-based zeolites were comprehensively reviewed, which mainly emphasized on the design of catalysts, reaction mechanism and deactivation mechanism. In 2019, Han et al.² published a comprehensive review on the application of metal oxide catalysts, acidic compound catalysts, metal-based zeolite catalysts, monolith catalysts and their reaction mechanism in NH₃-SCR. In addition, because of superior activity and hydrothermal stability in NH₃-SCR, many reviews were concentrated on the application of Cu-based zeolite catalysts,36 especially in Cu-SAPO-34,37 Cu-CHA38,39 and Cu-based small-pore zeolites.3,15,40 Besides, several reviews also gave detail information about the design and reaction mechanism of Fe-based zeolites for NH3-SCR.^{14,18,41,42} Besides, Andana et al.⁴³ summarized the recent research progress on the hybrid metal oxide-zeolite catalysts for low-temperature NH₃-SCR, which could enable the in situ NO oxidation over metal oxide and subsequently fast SCR over zeolite component through the "bifunctional mechanism".

For metal-based catalysts, many reviews focused on Mnbased oxides catalysts,44-47 Ce-based oxides catalysts,48 Febased oxides49 and the CeOx-MnOx mixture catalysts50 were published as those catalysts exhibited excellent lowtemperature (<100 °C) in NH₃-SCR. In addition, the latest progress on the vanadia-based and vanadia-free metal oxides catalysts had also been summarized.49,51 The deactivation mechanism of catalysts in NH3-SCR and corresponding strategies to enhance the poison-resistance of catalysts were also been summarized by researchers.^{19,52-55} The application of Density functional theory (DFT) in NH3-SCR were reviewed by Guan et al.56 to give clues on the mechanism studies. The influences of spatial confined structure on the catalytic performances of porous metal oxides, metal-based zeolite and metal organic framework catalysts were reviewed by Li et al.57 to give new insights for the designing of future NH₃-SCR catalysts.

Though many reviews were published for NH₃-SCR, reviews about the characterization methods dealing with the determination of active metal species in Cu-based or Fe-based zeolites for NH₃-SCR are scare. Therefore, this review systematically introduced several applicable characterization methods for the accurate determination of active metal sites over Cu-based and Fe-based zeolites in NH₃-SCR, such as UV-vis absorption spectra (UV-vis), temperature-programmed reduction with H₂ (H₂-TPR), X-ray photoelectron spectroscopy (XPS), X-ray absorption fine structure spectrum (XAFS), infrared spectroscopy (IR), electron paramagnetic resonance (EPR), Mössbauer spectroscopy and DFT calculations. In addition, the applications and limitations of different characterization methods in determining Cu-based or Fe-based zeolites are also compared and summarized. The investigation of NH_3 -SCR reaction mechanism based on the above characterization methods are also introduced, hoping to shed some light on the study of NH_3 -SCR mechanism over metal-based zeolites.

2 Characterization method of Cubased or Fe-based zeolites for NH₃-SCR

2.1 UV-vis

UV-vis absorption spectroscopy (UV-vis) is one of the powerful methods to determine the chemical state and content of metal species in zeolites.²⁰ For example, the existence of isolated Fe³⁺ species in tetrahedral or octahedral coordination, oligomeric Fe_xO_y species, and hematite-type Fe_2O_3 species can be qualitatively determined by the characteristic absorption band of UVvis spectra.58 According to literature,34,59,60 for Fe-based zeolites, the absorption band with wavelength lower than 300 nm in UV-vis spectra can be attributed to the isolated Fe³⁺ species, among which the UV absorption peak at 220-250 nm belongs to the four-coordinated isolated Fe³⁺ species while those at 250-300 nm are related to isolated Fe³⁺ species with higher coordination number such as octahedral-coordinated Fe³⁺ species. In addition, the absorption band at 300–400 nm is usually assigned to the charge transition peak of octahedral coordination aggregated Fe^{3+} species such as small Fe_xO_y species, while those with wavelength larger than 400 nm belongs to Fe₂O₃ nanoparticles. Based on the above assignments, the relative content of various Fe³⁺ species in zeolites can be estimated by the deconvolution of UV bands.34

Generally, for the UV-vis spectra of Cu-based zeolites, the absorption peak at about 210 and 280 nm can be attributed to charge transfer from lattice O^{2-} to Cu^{2+} , the UV band at *ca*. 750 nm is related to the d-d transitions of Cu^{2+} species with distorted octahedral coordination, all of those bands are

characteristic bands of isolated Cu^{2+} species.⁶¹⁻⁶⁴ In addition, the absorption bands at *ca.* 250 nm and 450 nm can be assigned to CuO_x species which are caused by the charge transfer and d– d transition of octahedral coordinated Cu^{2+} in CuO_x species.^{25,61,62,65} Similarly, the quantitative estimation of various Cu species can be achieved based on the above assignments, though the wavelengths of the same type of Cu species over different zeolites slightly change due to different interactions between Cu cations with zeolite framework.⁶²⁻⁶⁴

UV-vis spectroscopy conducting in situ is a powerful tool to provide information on the NH3-SCR mechanism of catalysts. Zhang et al.20 studied the NH3-SCR mechanism of two active Cu species, *i.e.*, isolated Cu²⁺ and [Cu(OH)]⁺ species, in Cu/SSZ-13 by in situ UV-vis with the aid of DFT calculations. They assigned the UV-vis band at 215 nm, 240 nm and 355 nm to $[Cu(OH)]^+$ species, isolated Cu^{2+} and dimer $[Cu_2O_2]^{2+}$ species, respectively, and found that two isolated [Cu(OH)]⁺ species could bridge to form a transient $[Cu_2O_2]^{2+}$ species upon O_2 activation, while isolated Cu²⁺ species remained unchanged. In addition, the [Cu(OH)]⁺ species exhibited stronger activity than isolated Cu2+ species during both reduction by NH3 and NO oxidation reactions. Moreover, the $[Cu_2O_2]^{2+}$ intermediates could be detected under low-temperature SCR conditions. Those results indicated that [Cu(OH)]⁺ species might play a more important role than isolated Cu²⁺ species in Cu/SSZ-13 for NH₃-SCR at low temperatures.

UV-vis spectra in combination with other techniques such as EPR, ICP-AES (inductively coupled plasma atomic emission spectroscopy) is an effective way to estimate the distribution of different metal species in zeolites.^{20,35,66} However, the estimation of the fraction for various Fe species or Cu species based on the deconvolution of UV-vis spectra is only a semiquantitative method due to the unknown extinction coefficients of different adsorption band currently.⁵⁹ Meanwhile, only Fe³⁺ and Cu²⁺ species can be observed by UV-vis spectra, Fe²⁺ and Cu⁺ species existing in zeolites are invisible in the wavelength range of 200–



Fig. 1 Summary on the determination of Cu or Fe species in zeolites by UV-vis spectra.

Table 1 The reduction process of Cu-based or Fe-based zeolites in H₂-TPR experiments

Zeolite	Reduction steps	Ref.
Cu-based zeolites	Two step reduction of isolated Cu^{2+} species: Cu^{2+} to Cu^+ : ~400 °C; Cu^+ to Cu^0 : 700–900 °C	27, 29, 74 and 77
	Two step reduction of $[Cu(OH)]^+$ species: $[Cu(OH)]^+$ to Cu^+ : ~250 °C; Cu^+ to Cu^0 : 360 °C	27, 74 and 77
	Directly reduction of CuO to Cu ⁰ : ~300 °C	27, 29 and 74
Fe-based zeolites (reduction temperature increases with Fe_xO_y particle size)	Two step reduction of isolated Fe^{3+} species: Fe^{3+} to Fe^{2+} : 380–430 °C; Fe^{2+} to Fe^{0} : 900–1000 °C	69, 71 and 72
	Reduction of small $Fe_x O_y$ species: 500–560 °C	24, 69 and 70–72
	Reduction of large Fe_2O_3 nanoparticles: 680–750 °C	24, 69 and 70-72
	Reduction of aggregated Fe_2O_3 or Fe_3O_4 particles: >1000 °C	34 and 73

800 nm in UV-vis experiments (for example, the adsorption band of Fe²⁺ species is located in the near infrared range around 1000 nm (ref. 66)). Moreover, only the coordination state of metal species can be obtained from UV-vis spectra, the detailed chemical structure, for example, whether the tetrahedral coordinated Cu²⁺ or Fe³⁺ species are in the framework or extraframework of zeolites cannot be distinguished.^{64,67} Therefore, the accurate determination of metal species in zeolites by UV-vis should be available with the aid of other methods, such as EPR, ICP-AES, H₂-TPR and IR experiments. In conclusion, the application and determination of Cu or Fe species in zeolites for NH₃-SCR by UV-vis are summarized in Fig. 1.

2.2 H₂-TPR

Temperature-programmed reduction with H_2 (H_2 -TPR) is a widely used method to differentiate chemical valence of Cu or Fe species in zeolites by the reduction reaction between hydrogen and metal cations. The reduction temperature can be used to distinguish the chemical valence of metal species, while the deconvoluted reduction peak area in the H_2 -TPR profiles can be used to estimate the content of metal species.^{27,68}

The reduction process of Fe-based zeolites are quite complex, as various kinds of Fe species such as isolated Fe³⁺ species, Fe_{2}^{2+} species, $Fe_{x}O_{y}$ clusters, large $Fe_{2}O_{3}$ nanoparticles can be easily formed in zeolites due to their similar energy of formation.13 However, by summarizing previous literature,24,69,70 the reduction peak of different Fe species can be roughly divided into several temperature ranges. The reduction of isolated Fe³⁺ at the ion-exchange sites of zeolites to Fe²⁺ are usually occurred at 380-430 °C, while the further reduction of these Fe²⁺ species to Fe⁰ can only take place at about 900–1000 °C due to the strong electrostatic interactions between Fe cations and the O-Al sites of zeolites.^{69,71,72} In addition, the reduction temperature of iron oxide clusters increases with their particle size, according to Brandenberger et al.69 Generally, the reduction of small Fe_xO_y clusters and large Fe_2O_3 nanoparticles are in the temperature range of 500-560 °C and 680-750 °C, respectively. In addition, some highly aggregated Fe₂O₃ or Fe₃O₄ particles are hard to be reduced during the H2-TPR experiments. Those Fe species can be reduced only by increasing the

reduction temperatures to about 1000 $^\circ C,$ which usually causes the collapse of zeolite framework. 34,73

For Cu-based zeolites, the reduction of isolated Cu²⁺ species at the ion-exchange sites of zeolites usually undergo two steps:^{27,29,74-76} the reduction of Cu²⁺ to Cu⁺, and further to Cu⁰. The reduction of two kinds of isolated Cu^{2+} species, *i.e.*, $Cu^{2+}-2Z$ and [Cu(OH)]⁺-Z (Z represents zeolite) happen at different temperatures due to their different stability in zeolites:27,74,77 the reduction of more stable Cu²⁺-2Z to Cu⁺ happens at about 400 °C, while that of less stable [Cu(OH)]⁺-Z species at about 250 °C with a further reduction peak of Cu⁺ to Cu⁰ at about 360 °C. The reduction of CuO nanoparticles in Cu-based zeolites are much easier than Cu cations. CuO nanoparticles could be directly reduced to Cu⁰ by hydrogen at around 300 °C.^{27,29,74} Occasionally, reduction peak at around 700-900 °C emerged at the H₂-TPR profiles of Cu-based zeolites, which could be attributed to the reduction of Cu⁺ at the ion-exchange sites of zeolites to Cu⁰ process, as the strong interactions between zeolite framework and Cu⁺ species hindered the reduction process.^{27,29} Table 1 summarizes the reduction steps of Cubased or Fe-based zeolites by H2-TPR experiments.

Calculating the H₂ consumption of each reduction peak by deconvolution the H₂-TPR profiles is an effective way to quantitatively estimate the content of various metal species in zeolites. The reduction process of different kinds of Cu species in Cu-based zeolites are shown in formula (1)–(4). Combining the reduction temperatures and H₂ consumption of various Cu species in H₂-TPR profiles, the content of various Cu species in Cu-based zeolites could be roughly estimated, according to previous literature.^{77–79}

$$Cu^{2+} + \frac{1}{2}H_2 \rightarrow Cu^+ + H^+ (H_2/Cu = 0.5)$$
 (1)

$$[Cu(OH)]^{+} + \frac{1}{2}H_{2} \rightarrow Cu^{+} + H_{2}O \ (H_{2}/Cu = 0.5)$$
 (2)

$$Cu^{+} + \frac{1}{2}H_{2} \rightarrow Cu^{0} + H^{+} \ (H_{2}/Cu = 0.5) \tag{3}$$

$$Cu^{2+} + H_2 \rightarrow Cu^0 + 2H^+ (H_2/Cu = 1)$$
 (4)

By conducting H₂-TPR experiments, Gao et al.⁷⁷ had semiquantitively determined the isolated Cu^{2+} and $[Cu(OH)]^+$ species and excluded the existence of CuO aggregated species in Cu/SSZ-13. Further, by combing with EPR and NH₃-SCR kinetic experiments, they investigated the influences of Si/Al ratio and Cu content in Cu/SSZ-13 on the NH₃-SCR mechanism and found that the six-membered rings (6MR) faces with 2 Al atoms in the CHA structure were the most favorable site in stabilizing Cu²⁺ ions, while Cu⁺ and [Cu(OH)]⁺ became the most stable Cu species in the absence of 2 Al sites. Song et al.27 also distinguished Cu²⁺ and [Cu(OH)]⁺ in Cu/SSZ-13 by H₂-TPR and further studied the hydrothermal stability of them in NH₃-SCR by combining EPR, DFT and kinetic reactions. They found that isolated Cu²⁺ species exhibited higher stability than [Cu(OH)]⁺ under hydrothermal aging conditions, which provided the atomic-level understanding of transformation of Cu species in NH₃-SCR. Those literature indicate that H₂-TPR is also an effective tool for the investigation of NH₃-SCR mechanism.

However, when H₂-TPR is used for the determination of metal species in zeolites, there are certain limitations: the reduction temperature of H₂-TPR is usually below 1000 °C, so it is incapable to effectively detect the metal species that are extremely difficult to reduce.³⁴ Moreover, the H₂-TPR experiments cannot detect the zero valent metals in the zeolites. Furthermore, though H₂-TPR can be used to determine both Cu^+ and Cu^{2+} or Fe²⁺ and Fe³⁺ species in Cu-based or Fe-based zeolites, the reduction peak could be affected by many factors.

Firstly, the differentiation of reduction peaks for various metal species in zeolites are sometimes difficult, as the reduction peak of the same type of metal species usually shift with the zeolite supports and preparation method. For example, the reduction temperature of Cu species in zeolites slightly changed when using different zeolites as support, as the reduction behaviors of metal species were sensitive to the zeolite support and local chemical environment of metal species.62,75,78,80 Secondly, the reduction temperature of metal species may also shift with the increasing of metal content, as the gradually formation of aggregation metal species may be undetectable in H₂-TPR or the overlapped reduction peaks may form a large broad peak.³⁵ Thirdly, the H₂O molecules adsorbed on the metal-based zeolites also affect the determination of H2-TPR, as the dehydration process of metal-based zeolites before the H₂-TPR experiments can cause the auto-reduction of metal species which eventually decrease the H₂ consumption in the H₂-TPR profiles.77,81 Lastly, the shape and area of reduction peak in the H₂-TPR experiments could also be affected by the heating rate of temperature-programmed process.82 Therefore, when H2-TPR is used to detect active metals on zeolites, it is necessary to select reasonable and repeatable experimental conditions, be careful in qualitative and quantitative analysis of H2-TPR results, and combine with other characterization methods to ensure the accuracy of the results.

2.3 XPS

X-ray photoelectron spectroscopy (XPS) based on photoelectric effect equation is often used to determine the composition and

chemical valence of elements on zeolite catalysts by exciting the inner electrons and measuring the binding energy of elements.⁸³

The XPS signal of Cu 2p in Cu-based zeolites are usually separated into Cu 2p_{3/2} and Cu 2p_{1/2} doublet structures (two peaks) due to the spin-orbit coupling. Generally, the $Cu^+ 2p_{3/2}$ and $2p_{1/2}$ signals are located at binding energy of *ca.* 932.5 \pm 0.2 eV and 952.3 \pm 0.2 eV, respectively, while Cu²⁺ 2p_{3/2} and 2p_{1/2} $_2$ signals are located at about 933.7 \pm 0.2 eV and 953.6 \pm 0.2 eV, respectively.84,85 In addition, the satellite peak at about 944 eV is also characteristic of Cu²⁺ species. However, the shift of binding energy for the same kind of Cu species are usually observed by many researchers, as the coordination structure and chemical state of Cu species can be significantly affected by the Cu loadings, preparation method and the zeolite supported of Cubased zeolites. Xu and co-workers⁸⁶ had observed the Cu²⁺ 2p_{2/3} and 2p_{1/2} signals at about 935.2 eV and 955.0 eV on Cu/Beta zeolites, which were related to the special local structure of Cu²⁺ species between Cu species and BEA framework. Moreover, previous researchers had different assignments for the binding energy at 928-940 eV of Cu 2p_{3/2} structure in Cu-based zeolites. Han and co-workers⁸⁷ assigned the two asymmetric signals at 933.5 eV and 936.5 eV to CuO species and isolated Cu²⁺ species in Cu/SSZ-13, which were supported by the Auger electron spectra and many other researchers.88-90 Therefore, the distinguish of Cu⁺ and Cu²⁺ species are not easy by XPS method, as the chemical state of Cu species are related to the support, which should be analyzed by combining several types of characterization methods.91

Similar to Cu 2p spectra, the XPS signal of Fe 2p spectra are also split into Fe $2p_{3/2}$ and Fe $2p_{1/2}$ doublet structures due to the spin–orbit coupling.^{84,92–94} Unlike Cu 2p spectra, the assignment of Fe 2p spectra are relatively clear, though slight shift of binding energy for different catalysts.^{92,94,95} Generally, the Fe²⁺ $2p_{3/2}$ and $2p_{1/2}$ signals are located at binding energy of *ca*. 710 eV and 723 eV with satellite peaks at *ca*. 715 eV and 729 eV, respectively, while Fe³⁺ $2p_{3/2}$ and $2p_{1/2}$ signals are located at about 711 eV and 724 eV with satellite peaks at *ca*. 719 eV and 733 eV, respectively.^{92,96} According to the above assignments, researcher had estimated the relative content of Fe³⁺ and Fe²⁺ species over Fe/Beta, Fe/ZSM-5 and Fe/MOR zeolites, which was in accordance with ⁵⁷Fe Mössbauer spectra results.⁹⁶

Based on XPS results of catalysts before and after hydrothermal aging treatment, Lee *et al.*⁸³ confirmed the formation of CuAl₂O₄ species (935 eV) in Cu/SSZ-13, Cu/UZM-35, Cu/Beta, Cu/ZSM-5 zeolites during the hydrothermal aging process, by combing with H₂-TPR, UV-vis and XANES experiments. They found that the extent of transformation of isolated Cu²⁺ species into CuO_x and CuAl₂O₄ species during hydrothermal aging process was higher in the order of Cu/SSZ-13 < Cu/UZM-35 < Cu/ Beta < Cu/ZSM-5, which was in line with the higher stability of Cu/SSZ-13 and Cu/UZM-35 than Cu/Beta and Cu/ZSM-5 in NH₃-SCR. Xu *et al.*⁸⁶ had compared the NH₃-SCR activity of copper and iron bimetal modified Beta zeolite (Cu–Fe/Beta) with that of Cu/Beta and Fe/Beta mono-component Beta zeolites and found that Cu–Fe/Beta exhibited higher low-temperature activity and wider temperature window than the rest two zeolites. Based on

	Attribution of XPS signals	Ref.
Cu-based zeolites	Characteristic of Cu ⁺ species: Cu ⁺ $2p_{3/2}$:	84-86
	935.2 eV and $955.0 eV$ in Cu/Beta	
	Characteristic of Cu^{2+} species: $Cu^{2+} 2p_{3/2}$: ~933.7 eV; $Cu^{2+} 2p_{1/2}$: ~953.6 eV; satellite peak: ~944 eV	84 and 85
	Different attributions in Cu/SSZ-13: CuO: 933.5 eV; isolated Cu ²⁺ species: 936.5 eV	87
	$Cu_2Al_2O_4$: ~935 eV	83
Fe-based zeolites	Characteristic of Fe^{2+} species: $Fe^{2+} 2p_{3/2}$: ~710 eV; $Fe^{2+} 2p_{1/2}$: ~723 eV; satellite peaks: ~715 eV and 729 eV	92 and 94–96
	Characteristic of Fe^{3+} species: $Fe^{3+} 2p_{3/2}$: ~711 eV; $Fe^{3+} 2p_{1/2}$: ~724 eV satellite peaks: ~719 eV and 733 eV	92 and 94–96

Table 2 The typical attribution of XPS signals in Cu-based or Fe-based zeolites

XPS measurement, they revealed that the dispersion state of active components and the ratios of Cu^{2+}/Cu^+ and $Fe^{3+/}Fe^{2+}$ in the Cu–Fe/Beta zeolite were increased when comparing with the other two zeolites due to the synergistic effect of copper and iron species, which was also supported by XRD, UV-vis and EPR results. Based on above researches, Table 2 summarizes the attribution of XPS signals in Cu-based or Fe-based zeolites.

Thought XPS can distinguish various Fe or Cu species by nondestructive testing which only need small amounts of sample (10-50 mg for zeolites), it can only detect elements of nanoscale thickness on the surface of zeolites, while the accurate determination of composition of the whole zeolites required element analysis by ICP-AES method.84,97,98 In addition, the automatic reduction of Cu^{2+} to Cu^{+} (or Fe^{3+} to Fe^{2+}) species was sometimes inevitable due to the ultra-high vacuum conditions of XPS determination, which would cause the deviation of XPS testing results from the actual state of zeolites.⁹⁹ Moreover, the binding energy of metal species may shift with zeolite supports due to the different interactions between metal species and zeolite framework.89,96 Therefore, the accurate analysis of various metal species by XPS should take the above factors into account and often needs to be carried out by combining other characterization methods such as ICP-AES, EPR, Auger electron spectra and UV-vis spectra.83,90,93,97,100

2.4 XAFS

The X-ray absorption fine structure spectroscopy (XAFS) is an atomic-scale tool to study the local structure and chemical state of metal species in zeolites.^{101–103} When the energy of X-ray resonates with the ionization energy of the inner layer electron of atoms, the electron is excited to form a continuous spectrum (XAFS). The X-ray absorption near-edge structure (XANES) consists of the regime from -10 eV below to *ca*. 50 eV above the edge energy E_0 , which can be used to determine the electronic state of the absorbing atom, such as oxidation number and the geometric structure.¹⁰⁴ The extended X-ray absorption fine structures (EXAFS) comprises the regime from about 50 eV to about 1000 eV above E_0 , which can be used to

determine the local structure of atoms, as EXAFS can provide the interatomic distances and coordination numbers for several coordination shells around the absorbing atom.¹⁰⁴

In recent years, XAFS has been widely used to study the active sites of metal-based zeolites in NH3-SCR reactions. Deka et al.26 had studied the local environment of copper species in Cu/SSZ-13 under realistic NH₃-SCR conditions by in situ XAFS and in situ XRD experiments, and confirmed that the isolated Cu²⁺ species located in the double-six-ring (D6R) subunit of CHA structure were the main active sites for NH₃-SCR. In addition, they found that the isolated Cu²⁺ species suffered from a conformational change in the local geometry from a planar form to a distorted tetrahedron due to a preferential interaction with NH₃ at low temperatures, which process resulted in the stymieing of activity. In contrast, due to the weak interactions between the isolated Cu²⁺ species and NH₃, the local structure of isolated Cu²⁺ species remained unchanged at high temperatures, which results in the high activity of Cu/SSZ-13 in NH₃-SCR. Korhonen et al.25 also found that isolated Cu2+ species were the main active sites in NH₃-SCR over Cu/SSZ-13 zeolites based on EXAFS experiments.

McEwen et al.28 had explored the Cu oxidation state and coordination environment in Cu/SSZ-13 zeolites during the NH₃-SCR reactions by operando XAFS experiments and found that, tetrahedral coordinated Cu²⁺ species dominated in Cu/ SSZ-13 under fast NH_3 -SCR ($NO_2/NO_x = 0.5$) and NO_2 -SCR $(NO_2/NO_x = 1)$ reaction conditions, while both Cu^+ and Cu^{2+} species existed in Cu/SSZ-13 zeolite under standard NH₃-SCR $(NO_2/NO_r = 0)$ reaction conditions, which indicated that partial reduction of copper species occurred under the standard NH3-SCR atmosphere. As shown in Fig. 2, Lomachenko et al.¹⁰⁵ had monitored the oxidation state, mobility of Cu species over Cu-CHA zeolites during NH₃-SCR reactions at 150-400 °C range by operando XAFS experiments and unambiguously identified two distinct regimes for the catalytic mechanism of Cu active sites. In the low temperature range (<200 °C), Cu⁺ (m-Cu(1) complexes) and Cu²⁺ species (Z-Cu(II) and m-Cu(II) complexes) were the main catalytic active centers, which were solvated by



Fig. 2 The relationship between the relative percentages of Z–Cu(II), m-Cu(II) and m-Cu(I) species and the NH₃-SCR activity in different temperatures. Z–Cu(III) stands for the sum of Z–[Cu(II)OH⁻] and Z–[Cu(II)NO₃⁻] complexes, while m-Cu(II) represents the sum of mobile [Cu(II)(NH₃)₄]²⁺ and [Cu(II)(H₂O)₆]²⁺ complexes. m-Cu(II) represents the mobile [Cu(II)(NH₃)₂]⁺ complexes in Cu/SSZ-13 zeolites (atoms color code: Cu: green, O: red, Al: yellow, Si: gray, N: blue, H: white).¹⁰⁵ (with permission from ACS publications).

NH₃ due to the strong coordination between NH₃ and copper species. In the middle and high temperature range (250–400 $^{\circ}$ C), the main catalytic active centers were isolated Cu²⁺ species (Z–Cu(II) complexes) which were coordinated with zeolite framework.

The detail understanding of the redox cycle of active metal species is important for the revealing of NH₂-SCR reaction mechanism, as NH₃-SCR is a redox reaction. Ueda et al.¹⁰⁶ had investigated the redox cycle of Cu species in Cu/ZSM-5 for NH₃-SCR based on in situ XAFS experiments. They found that Cu²⁺ species could be slowly reduced to Cu⁺ species by NH₃ flow, which process could be accelerated by adding NO to the NH₃ flow. However, for the oxidation half-cycle, the complete oxidization of Cu⁺ to Cu²⁺ species could only be achieved by the NO and O₂ mixture flow but oxygen alone. Those results indicated that the oxidation half-cycle of Cu⁺ to Cu²⁺ process was more difficult than the reduction half-cycle, which was the ratelimiting step for the whole NH₃-SCR reactions. Further, Gao et al.32 had studied the detailed pathway of the oxidation halfcycle on Cu/SSZ-13 by in situ EXAFS experiments combined with DFT calculations, and confirmed that for NH₃-SCR reactions at low temperatures, the oxidation half-cycle of Cu(1) to $Cu(\pi)$ requires the participation of two isolated Cu^+ species by forming $[Cu^{I}(NH_{3})_{2}]^{+}-O_{2}-[Cu^{I}(NH_{3})_{2}]^{+}$ as intermediates.

Lercher *et al.*¹⁰⁷ had studied the redox process of Fe/Beta in NH₃-SCR by determining the fraction of Fe²⁺ and Fe³⁺ species through the combination of XANES and Mössbauer spectroscopy, they found that the distribution of Fe²⁺ and Fe³⁺ in Fe/BEA zeolites depended mainly on both the Fe content in zeolites and the conditions of the thermal treatment. In addition, they also revealed that the ion exchanged isolated Fe²⁺/Fe³⁺ species are reversibly oxidized and reduced under real NH₃-SCR conditions, which were the main active sites for NH₃-SCR. Doronkin *et al.*¹⁰⁸ had investigated the structure of iron sites in Fe/Beta and



Fig. 3 Summary on the studying of NH₃-SCR mechanism in Cu/zeolite by XAFS.

 Table 3
 Assignment of IR bands of NO adsorption complexes in Fe/H-SSZ-13 zeolite according to Szanyi et al.¹²⁵ (with permission from RSC Publications)

Adsorption center	P _{NO}	Low	Medium	High
Fe ²⁺ in 8 MR of CHA	Ads. complex	Fe ²⁺ (NO)	$Fe^{2+}(NO)_2$	$Fe^{2+}(NO)_3$
	IR peak position	1900	1//1	1801 1810
Fe ²⁺ in 6 MR of CHA	Ads. complex IR peak position	Fe ²⁺ (NO) 1884	1852 Fe ²⁺ (NO) 1884	1917 Fe ²⁺ (NO) 1884

Table 4	The assignment	of IR bands after CO	adsorption over	several Fe-based zeolites
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FTIR bands after CO adsorption over Fe-b	ased zeolites (cm	-1)				
Fe ²⁺ -CO	Fe ²⁺ -(CO) ₂	OH–CO adducts	Fe ³⁺ -OH…CO	Al ³⁺ -CO complex	FeO _x -(CO)	Ref.
2190	_	2175	2157	2225	_	58
2187, 2195 (in small cavities); 2196 (in large cavities)	2188	2173	_	—	—	122
2198 (in 6 MR) 2207 (in 8 MR)	_	2175	_	2221 2231	2129 2148 2177	125
	FTIR bands after CO adsorption over Fe-b Fe ²⁺ -CO 2190 2187, 2195 (in small cavities); 2196 (in large cavities) 2198 (in 6 MR) 2207 (in 8 MR)	FTIR bands after CO adsorption over Fe-based zeolites (cm Fe^{2+} -CO Fe^{2+} -(CO)22190—2187, 2195 (in small cavities); 2196 (in2188large cavities)2198 (in 6 MR)2198 (in 6 MR)—2207 (in 8 MR)—	FTIR bands after CO adsorption over Fe-based zeolites (cm^{-1}) Fe^{2+}-COFe^{2+}-(CO)_2OH-CO adducts2190—21752187, 2195 (in small cavities); 2196 (in large cavities)218821732198 (in 6 MR)—21752207 (in 8 MR)—2175	FTIR bands after CO adsorption over Fe-based zeolites (cm^{-1}) Fe^{2+}-COFe^{2+}-(CO)_2OH-CO adductsFe^{3+}-OH…CO2190—217521572187, 2195 (in small cavities); 2196 (in large cavities)21882173—2198 (in 6 MR)—2175—2207 (in 8 MR)—2175—	FTIR bands after CO adsorption over Fe-based zeolites (cm^{-1}) OH-CO adducts Al ³⁺ -CO complex Fe ²⁺ -CO Fe ²⁺ -(CO) ₂ OH-CO adducts Fe ³⁺ -OH…CO Al ³⁺ -CO complex 2190 — 2175 2157 2225 2187, 2195 (in small cavities); 2196 (in large cavities) 2188 2173 — — 2198 (in 6 MR) — 2175 — 2221 2207 (in 8 MR) — 2175 — 2231	$\begin{array}{c c c c c c c c c c c c c c c c c c c $

copper sites in Cu-SAPO-34 zeolites during the real NH₃-SCR conditions by operando spatially-resolved and time-resolved XAFS experiments, respectively. They found strong gradients of Fe and Cu oxidation state along the Fe/Beta and Cu-SAPO-34 catalyst bed, respectively. By detailed studies on the change tendency of relative percentages of Fe and Cu oxidation state in NH₃-SCR reactions over Fe/Beta and Cu-SAPO-34 catalyst, respectively, they concluded that the re-oxidation of Cu or Fe in zeolites was the rate-limiting step in NH3-SCR. Dahl et al.¹⁰⁹ had studied the NH₃-SCR reaction mechanism over Fe-Beta zeolites by in situ XANES and EXAFS experiments. They also found a relation between the oxidation state of iron and the NH3-SCR catalytic activity of Fe/Beta zeolites and concluded that isolated iron species were the active sites while the re-oxidation of iron species was one of the rate-limiting steps in NH₃-SCR.

It is worthy to note that the chemical state of Cu or Fe species in zeolites during the NH3-SCR reactions will undergo successive reduction and oxidation steps so as to catalyze the redox process. Therefore, in most of the literature, the investigation of chemical state of the metal species in zeolites were conducted by in situ or operando XAFS under NH₃-SCR reaction conditions, so as to reveal the detail reaction mechanism of NH₃-SCR. However, the ex situ XAFS experiment of metal-based zeolites can still provide valuable information to NH₃-SCR mechanism. Firstly, the ex situ XAFS experiment can be used to determine the state of metal species in the as-prepared catalysts, supported by other characterization methods such as UV-vis, H₂-TPR, etc.¹¹⁰ Korhonen et al.²⁵ compared the EXAFS spectra of Cu/ SSZ-13 zeolites before and after calcination and found the

coordination number of Cu²⁺ ions in SSZ-13 reduced from 4 to 3, along with the decrease of average distance of Cu-O distance from 2.02 Å to 1.93 Å, which indicated that the state of Cu in SSZ-13 is sensitive to reaction conditions. In addition, the good fitness of experimental EXAFS and calculated ones confirmed the validity of the proposed local structure of the isolated Cu²⁺ species in SSZ-13, which is important for the further studying of NH₃-SCR mechanism. Secondly, by comparing the ex situ XAFS results of catalysts treated at different gas and temperature conditions, it is possible to speculate the reaction mechanism of catalysts in NH₃-SCR. Deka *et al.*²⁶ had studied the Cu K-edge XANES spectra of Cu-SSZ-13 after calcination and under NH₃-SCR conditions at different temperatures (125-300 °C). They found that the local environment of isolated Cu²⁺ species (located on the plane and slightly distorted from the center of the D6R subunits of CHA) under NH₃-SCR reaction at 300 °C was similar to that seen after calcination, whereas a conformational change from a square planar to a distorted tetrahedral type structure was observed for isolated Cu2+ species at 125 °C in NH₃-SCR conditions due to a direct interaction of NH₃ with copper, according to XANES and EXAFS spectra results. Those results indicated that the reaction mechanism of Cu-SSZ-13 in NH₃-SCR changed with reaction temperatures, which was further confirmed by Lomachenko et al.111 through operando XAFS and Emission Spectroscopies. In conclusion, the application of XAFS over Cu-based zeolites for investigating NH3-SCR mechanism is summarized in Fig. 3.

The fine structures at X-ray absorption edges contain information about the geometrical and electronic structure of

Table 5 The assignment of FTIR bands after CO adsorption over several Cu-based zeolites									
	FTIR bands	after CO adso	rption over Cu-based	l zeolites (cr	n ⁻¹)				
Zeolite	Cu ⁺ -CO	Cu^+ -(CO) ₂	Cu ⁺ -(CO) ₃	Cu ²⁺ -CO	OH ⁻ -CO	$[Cu(OH)]^+ \cdots CO$	Al ³⁺ CO	CuO _x ····CO	Ref.
Cu-SSZ-13	2155	2150, 2178	2134, 2169, 2194	_	_	2207	2220	_	131
Cu-SSZ-13	2158	2148	_	_	2177	_	_	_	127
Cu-SSZ-13	2135, 2154	2178	_	2220	_	_	_	_	129
Cu/SAPO-34	2154	2147, 2178	2139, 2163, 2187	_	2171	_	_	2131	127
Cu/ZSM-5	2158	2150, 2178	2134, 2166, 2192	_	_	_	_	_	131 and 132
Cu/Beta	2158, 2153	2152, 2180	2134, 2168, 2193	_	_	_	_	_	131
Cu/MOR	2159	2152, 2180	2146, 2167, 2193	_	_	_	_	_	133
Cu/FER	2157	2149, 2178	2135, 2170, 2191	_	_	_	_	_	134

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absorbing atoms, which has been widely used in the study of NH₃-SCR reaction mechanism over metal-based zeolite catalysts.^{101,112-114} However, the major disadvantage of XAFS experiment is that the signals of all absorbing atoms of one type in the sample may overlap at the edge, which made it difficult to distinguish the individual signals belonging to different species when the sample contains an element in several different atomic environments.¹⁰² Another disadvantage of XAFS is that the accessibility of synchrotrons of X-ray is not easy, as beam times are scarce which need to be scheduled months ahead.¹⁰⁴

2.5 FTIR spectroscopy

Infrared (IR) spectroscopy can detect the framework vibration of zeolites, the chemical bond vibration of metal cationic in zeolites and the vibration of bonds between adsorbent and zeolite framework, so as to analyze the structure of metal-based zeolites, or capture the surface adsorption groups and active intermediates on catalysts.¹¹⁵⁻¹¹⁸ In NH₃-SCR, the Fourier transform infrared spectra (FTIR) after *in situ* adsorption of NO or CO (FTIR of adsorption NO or CO) are often used to explore the status of metal active species on the zeolite catalysts,¹¹⁹⁻¹²² as CO and NO molecules can form coordination complexes with metal cations which can be detected by infrared spectroscopy.

The FTIR of adsorption NO or CO experiments can be used to selectively determine the Fe²⁺ species in zeolites, as the adsorption of NO or CO on Fe³⁺ are too weak to be detected.²⁴ Though the pre-treatments of Fe-based zeolites for FTIR experiments under high temperature and ultra-high vacuum (about 300–500 °C and 10⁻⁵ Pa) may cause the automatic reduction of Fe³⁺ species to Fe²⁺ species, thus bringing about the deviation of FTIR spectra from the actual one, the FTIR spectra of adsorption NO or CO can still provide key information about the catalysts.^{115,123,124}

Gao et al.^{24,125} showed that NO could coordinate with Fe²⁺ species to form a variety of Fe complexes on Fe/SSZ-13 zeolites: the mononitrosyl Fe²⁺-NO species (1885 cm⁻¹) formed in the six-membered rings (6MR) of CHA structure, the dinitrosyl Fe²⁺-(NO)₂ (1850 and 1772 cm⁻¹) and trinitrosyl Fe²⁺-(NO)₃ (1916, 1810 and 1797 cm⁻¹) species formed in the eightmembered ring (8MR) windows of CHA cage. By comparing the chemical statues and content of Fe²⁺ species before and after hydrothermal aging treatments, the migration and transformation behaviors of Fe²⁺ species in Fe/SSZ-13 zeolites were also clarified by Gao et al.,²⁴ which suggested that even hydrothermal aging at 600 °C could result in the aggregation of Fe²⁺ species and the formation of FeAlO_x clusters with low reducibility in NH3-SCR. Szanyi and co-workers125 found two kinds of mononitrosyl Fe²⁺-NO species existed in Fe/SSZ-13 zeolites by FTIR of NO adsorption experiments, one was the Fe²⁺-NO species in the restricted environment (at the ion-exchange sites in six-membered rings of CHA structure, with FTIR signal at 1880 cm^{-1}) which were thermodynamically stable, the other was the unstable Fe²⁺-NO species in the open environment (in the CHA cages, with FTIR signal at 1900 cm^{-1}), which would gradually transform into trinitrosyl Fe²⁺-(NO)₃ complex, as supported by the shift of infrared absorption band to 18001830 cm⁻¹. According to Szanyi *et al.*,¹²⁵ the assignment of FTIR bands after NO adsorption over Fe-based H-SSZ-13 zeolites are summarized in Table 3. The Fe²⁺ species located in the eightmembered ring (8MR) of the large CHA cage could form three types of Fe²⁺–(NO)_x species with NO (*i.e.*, Fe²⁺–NO, Fe²⁺–(NO)₂ and Fe²⁺–(NO)₃) by increasing the adsorption pressure of NO, whereas only mononitrosyl Fe²⁺–NO species could be formed in Fe²⁺ species located in the six-membered rings (6MR) of double six-member (D6R) prisms due to the strong electrostatic interactions between Fe²⁺ ions and zeolite framework.

CO is a sensitive probe for the characterization of Fe²⁺ species over zeolites. Kim and co-workers58 had investigated the distribution of Fe species on Fe/Beta zeolites by IR spectroscopy of adsorbed CO, they found that the primary bands at 2190, 2175 and 2157 cm^{-1} were attributed to Fe^{2+} -CO species, the acidic OH-CO adducts and to CO interacting with Fe³⁺-OH species, respectively, as the direct interactions between Fe³⁺ and CO were too weak to form Fe³⁺⁻CO species.¹²⁶ In addition, the weak bands at about 2225 cm⁻¹ and 2130 cm⁻¹ were attributed to Al³⁺-CO complex and physiosorbed CO, respectively. Moreover, by introducing O2 onto the surface of Fe/Beta zeolites, the fraction of Fe²⁺ species (reflecting by the Fe²⁺-CO bands at 2190 cm⁻¹) apparently decreased correspondingly with the dramatically increasing of Fe³⁺ species (representing by the Fe^{3+} -OH···CO band at 2157 cm⁻¹), which suggested the oxidation of Fe^{2+} species to Fe^{3+} species in the presence of O₂ over Fe/ Beta zeolites. Malpartida and co-workers¹²² also found that CO could distinguish two kinds of Fe²⁺ species in Fe/FER zeolites by IR spectroscopy of adsorbed CO under dynamic vacuum: one is the mono-carbonyl Fe²⁺-CO species (with strong bands at 2196 cm^{-1}) formed by CO with the most abundant iron sites at large cavities of ferrierite zeolites, which could be transformed to di-carbonyl species by increasing CO pressure; the other is the mono-carbonyl Fe²⁺–CO species (with weak IR bands at 2187 cm^{-1}) formed by CO coordinating with less abundant iron sites located in more confined sites, which were more stable than the former one and couldn't be converted to di-carbonyl species. Szanyi et al.125 also investigated the FTIR spectra after CO adsorption over Fe/SSZ-13 zeolites, in which several IR bands were different from the above-mentioned Fe-based zeolites, which was reasonable as the coordination environments of Fe²⁺ species in different zeolites were slightly changed. By summarizing the above literature, the assignments of IR bands after CO adsorption over several Fe-based zeolites are summarized in Table 4.

Similar to Fe-based zeolites, IR spectroscopy of adsorbed CO can be used to selectively determine the Cu⁺ species in Cu-based zeolites, while the adsorption of CO on Cu²⁺ species are much weak.^{127,128} According to Corma and co-workers,¹²⁷ the IR absorption band of the mono-carbonyl Cu⁺–CO complex formed by CO interacting with Cu⁺ at the ion exchange sites of Cu/CHA zeolites appeared at about 2155 cm⁻¹, while the absorption peak at about 2180 cm⁻¹ could be attributed to the asymmetric stretching of the bicarbonyl Cu⁺–(CO)₂ complex formed by two CO molecules with one Cu⁺ species. Szanyi *et al.*¹²⁹ had studied the distribution of Cu species on Cu/SSZ-13 by IR spectroscopy and found that the adsorbed CO at room temperature primarily

Table 6 The assignment of FTIR bands after NO adsorption over several Cu-based zeol	lites
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ETID bands after NO adsorption over Cu based goolites (am^{-1})

	The bands after no adsorption over ou based zeones (chr.)						
Zeolite	Cu ⁺ -NO	Cu ⁺ -(NO) ₂	Cu ²⁺ -NO	Cu ²⁺ -(NO) ₂	[Cu(OH)]⁺… NO	$\begin{array}{l} [\text{Cu-O-Cu}]^{2+} \cdots \\ (\text{NO})_2 \end{array}$	Ref.
Cu/SSZ-13	1809	1826, 1728	1890	_	_	_	131
Cu/SSZ-13	1803, 1816	1663, 1800, 1654, 1783	1925, 1947, 1960, 1965, 1977	1801, 1892, 1869, 1813, 1874	1795, 1788	—	127
Cu/SAPO- 34	1811, 1821	1720, 1831, 1714, 1828	1907, 1940, 1943, 1968	1809, 1888, 1802, 1868	1790, 1798	1712, 1887	127
Cu/ZSM-5	1813	1730, 1825	1921, 1912, 1905, 1895	_	_	_	131 and 135
Cu/Beta	1802, 1815	1828, 1734	1912, 1903, 1895	_	—	_	131 and 136
Cu/MOR	1813	1730, 1828 (main channel); 1785, 1870 (side pocket)	1960, 1938, 1921, 1909, 1895	_	_	_	135 and 137

formed Cu^+ -CO species, but Cu^+ -(CO)₂ and Cu^{2+} -CO species could also be formed when excessive CO were dosed.

In contrast to IR spectroscopy of CO adsorption, IR spectroscopy of NO adsorption can detect both Cu²⁺ and Cu⁺ species in Cu-based zeolites, due to the strong interactions between NO and copper cations.^{127,129,130} Concepcion *et al.*¹²⁷ found that only the mono-nitroso complex Cu²⁺-NO could be formed on Cu/ SSZ-13 and Cu/SAPO-34 zeolites due to the strong coordination between isolated Cu²⁺ and framework oxygen of zeolites, which exhibited two IR bands at around 1925 cm⁻¹ and 1950 cm⁻¹, attributing to two kinds of Cu²⁺-NO complexes formed by NO reacting with Cu²⁺ species located in the sixmembered and eight-membered rings of CHA structures, respectively. In contrast, various nitro complexes could be formed between NO and Cu⁺ species over Cu/SSZ-13 and Cu/ SAPO-34 zeolites: the infrared absorption peak at 1805-1820 cm⁻¹ and 1660-1720 cm⁻¹ could be assigned to mononitroso Cu⁺-NO complex and di-nitroso Cu⁺-(NO)₂ complex, respectively. In addition, NO could also coordinate with hydrated Cu²⁺ species ([Cu(OH)⁺]) to form the IR band at around

1790 cm⁻¹, which was confirmed by a newly formed hydroxyl vibrational absorption peak at 3668 cm^{-1} . Moreover, NO could also interact with dimeric Cu²⁺ species ([Cu-O-Cu]²⁺) to form two kinds of IR absorption bands at 1712 cm⁻¹ and 1887 cm⁻¹, which were attributed to the adsorption of NO on the Cu^{II}-O bridge bonds, and the direct adsorption of NO on Cu^{II} in [Cu–O– Cu]²⁺ dimers, respectively. Giordanino et al.¹³¹ summarized the FTIR bands after CO adsorption or NO adsorption over different Cu-based zeolites and revealed that the preparation method of catalysts and testing conditions (temperature, NO pressure, oxidation or reduction atmosphere) of FTIR experiments could resulted in slightly shift of FTIR bands for Cu-NO or Cu-CO complexes over different Cu-based zeolites. Base on above literature, the typical assignments of FTIR bands after CO adsorption or NO adsorption over different Cu-based zeolites are summarized in Tables 5 and 6, respectively.

Infrared spectroscopy of NO or CO adsorption is a highly valuable tool to provide information about the chemical nature of metal species in zeolites, such as the oxidation state, coordination environment, which are important in NH_3 -SCR



Fig. 4 Summary on the EPR determination and quantification of Cu species in Cu/zeolite.



Fig. 5 Mössbauer spectroscopy of the ambient 57 Fe/SSZ-13 sample measured at 8 K. Peak fitting results and percentages of different components, Fe(III)-P, Fe(III)-P, Fe(III)-M are also displayed¹⁴⁴ (with permission from ACS publications).

reactions.115,138,139 Through in situ adsorption of CO and NO infrared experiments, researchers had detailly investigated the distribution of Cu species on Cu/SSZ-13 zeolites under different pretreatment conditions, which provided valuable information for the understanding of detailed NH₃-SCR reaction mechanism.7,14,127,129 However, the quantitative of various metal species by IR bands are difficult, as the unknown extinction coefficients of different adsorption band for metal species. In addition, the assignments of IR bands for NO or CO adsorption over different zeolites should be careful, as the interactions between zeolites with different framework and metal species were different, which would cause the shift of IR bands.115 Moreover, the overlap of absorption peaks may occur at high adsorption pressure of CO or NO or when high loading of metal species was achieved at zeolites, which would make the assignment of IR bands difficult.1,79 Therefore, care must be taken when general conclusions are drawn about the adsorption and reactive properties of metal species based on infrared spectroscopy of NO or CO adsorption in zeolites, which may should be supported by other characterization methods.

2.6 EPR

Electron paramagnetic resonance (EPR) is a magnetic resonance technology based on the magnetic moment of unpaired electrons which move around the nucleus and spin at the same time, resulting in electric current and magnetic moment.¹⁴⁰ Under an external electromagnetic field, the electrons with low energy levels can be excited to high energy levels by absorbing microwave energy, resulting in electron paramagnetic resonance. The *g* factor (spectral splitting factor) in paramagnetic field information can be used to analyze the chemical environments of metal atoms.^{21,43}

EPR spectroscopy has been successfully used to characterize the coordination environment and local structure of copper species in Cu-based zeolites.²² As Cu⁺ lacks paramagnetic electrons, $[Cu(OH)]^+$ has the pseudo Jahn-Teller effect, CuO_x clusters and [Cu–O–Cu]²⁺ have antiferromagnetic interactions, these copper species are EPR silent species.27 However, under hydration, [Cu(OH)]⁺ species can be converted into $[Cu(OH)(H_2O)_5]^+$ species with EPR activity and thus be detected by EPR. In contrast, when dehydrated, $[Cu(OH)(H_2O)_5]^+$ species can be transformed into [Cu(OH)]⁺ species, or be automatically reduced to Cu⁺ species or be condensed to form [Cu-O-Cu]²⁺ or CuO_r species, which are all EPR silent species. On the other hand, isolated Cu²⁺ species, either in the hydrated form $([Cu(H_2O)_6]^{2+}$ or $[Cu(OH)(H_2O)_5]^{+}$) or dehydrated form (Cu^{2+}) , are paramagnetic and can be detected by EPR.^{27,77} Therefore, the relative content of [Cu(OH)]⁺ and isolated Cu²⁺ species on Cubased zeolites can be quantitatively calculated by EPR spectroscopy through determining the Cu-based zeolites under dehydration and hydration conditions, as described in Fig. 4.

Gao *et al.*²⁷ had quantitatively determining the content of various Cu species on Cu/SSZ-13 zeolites by combing EPR experiments under hydrated and dehydrated conditions with ICP-AES method. As summarized in Fig. 5, firstly, the content of isolated Cu²⁺ species can be calculated by EPR spectra of dehydrated Cu/SSZ-13 zeolites. Secondly, the total content of



Fig. 6 Summary on the determination of Fe species in Fe/zeolite by Mössbauer spectroscopy.

 Table 7
 Comparison on the experimental and computational results

 for NO frequencies in different Cu–NO complexes in FTIR spectra¹²⁴
 (with permissions from ACS publications)

NO frequency (cm^{-1})	Experimental results	Computational results
Cu ²⁺ -NO [Cu(π)OH] ⁺ -NO Cu ⁺ -NO Cu-N ₂ O Cu ⁺ -NO ⁺	$1850-1950 \\ 1870-1915 \\ 1770-1808 \\ \sim 2250 \\ 2160-2170$	1895–1932 1874, 1907 1794, 1788, 1795 2367, 2339, 2362 —

isolated Cu²⁺ species and [Cu(OH)]⁺ species can be measured by EPR spectra of hydrated Cu/SSZ-13 zeolites; then the content of [Cu(OH)]⁺ species on Cu/SSZ-13 zeolites can be calculated by the difference between the above two EPR spectra. Thirdly, the total content of all the Cu species on Cu/SSZ-13 zeolites can be measured by ICP-AES analysis. Therefore, the total content of copper species without EPR activity (such as Cu⁺, [Cu–O–Cu]²⁺ and CuO_r) can be calculated by combining the quantitative results of ICP-ASE and EPR experiments. Based on the quantitative determining of various Cu species on Cu/SSZ-13 zeolites, Gao et al.27 found that the isolated Cu2+ species showed good hydrothermal stability in NH₃-SCR. In contrast, during the hydrothermal aging process, the [Cu(OH)]⁺ species in Cu/SSZ-13 zeolites would gradually transform into CuO_r species, which had almost no NH₃-SCR activity but high activity to the side reactions of ammonia oxidation, and eventually cause the decrease of NH₃-SCR activity.

EPR spectra can also be used to distinguish the location and distance of isolated Cu²⁺ species. Gao *et al.*⁷⁸ had estimated the Cu–Cu distance of isolated Cu²⁺ ions in Cu/SSZ-13 zeolite based on the line broadening of EPR spectra. They found that the Cu–Cu distance was greater than 20 Å at low copper loadings, indicating that there was allowed only one Cu²⁺ ions within one

hexagonal unit cell. As the Cu loading increased, the Cu–Cu distance decreased significantly, indicating that several Cu²⁺ ions were located in the large CHA cages and were close to the eight-membered rings.

In Fe-based zeolites, EPR spectra can be used to selectively detect Fe³⁺ species, as Fe²⁺ was silent in EPR spectra due to the lack of paramagnetic electrons. According to literature,^{73,141,142} the EPR signal at g = 4.3 can be attributed to the tetrahedral Fe^{3+} species in the framework of zeolites, while the signa at g =6.0 and 8.8 are attributed to the distorted tetrahedral Fe³⁺ species and octahedral coordinated Fe³⁺ species, respectively. In addition, the highly symmetric octahedral coordinated Fe^{3+} , which are the predominant active species in NH₃-SCR, has characteristic EPR signals at g = 2.0; while the aggregated Fe_xO_y species show EPR characteristic signals at g = 2.3. Li *et al.*⁷³ had prepared Fe-ZSM-5 zeolites with different iron content by onepot method, and found that the NH₃-SCR catalytic activity of Fe-ZSM-5 were positively correlated with the EPR iron species at g = 2.0 in the EPR spectra, which supported the above assignments. However, Shen et al.141 had investigated the distribution of Fe³⁺ species in Fe/Beta zeolites by UV-vis and in situ EPR spectra and found that the isolated Fe³⁺ species in distorted tetrahedral (g = 6) and octahedral (g = 8.8) environments showed higher NH3-SCR activity, while those in tetrahedral framework environments (g = 4.3) exhibited lower activity. The controversial results of EPR spectra over different Fe-based zeolites demonstrates that the differences in zeolite support, in the type and content of iron species and in the different experimental conditions could bring in discrepancies in the EPR spectra, which should be carefully analyzed considering the detailed experimental conditions of EPR spectra or by combining with other characterizations such as UV-vis, FTIR or XAFS.13

EPR is a powerful tool for determining metal species in zeolites with high sensitivity, which can provide qualitative and





View Article Online Review

quantitative information on the oxidation state and chemical environment of paramagnetic metal ions by combining with other characterization methods such as ICP and UV-vis.29 However, there are still some limitations in the application of EPR spectra. Firstly, the EPR spectra with high resolution can only be obtained under ultra-low temperature of about 155 K for Cu-based zeolites78 and about 7 K for Fe-based zeolites,24 in order to avoid the signal broadening due to the migration of metal species and the anti-ferromagnetic interactions. Secondly, EPR spectra of metal-based zeolites are highly sensitive to water and paramagnetic species, so the testing conditions of EPR spectra should be strictly controlled.²¹ Thirdly, when the structure of zeolite support changes, the g value of EPR signal for the same kind of metal species may shift due to different interactions between metal species and zeolites, which made the assignment of EPR signal difficult.¹⁰⁹ Therefore, the EPR spectra should be analyzed carefully according to the preparation method, zeolite support and metal content of catalysts, or by combining with other characterizations.

2.7 Mössbauer spectroscopy

Mössbauer spectroscopy is a kind of gamma ray spectrum based on "Mössbauer effect", i.e., "the emission and subsequent resonant absorption of nuclear gamma rays by the nuclei of certain atoms embedded in a solid material".143 When the energy of the gamma ray equal to the energy of nuclear energy level transition, the resonant absorption phenomenon can be observed in Mössbauer spectroscopy. Mössbauer spectroscopy can be used to study the chemical valence or oxidation state, magnetic properties, coordination numbers and electron density of specific atoms. However, though the "Mössbauer effect" of more than 80 isotopes is measurable, only two of them (⁵⁷Fe, ¹¹⁹Sn) are applied in practice due to the restrict testing conditions and equipment.143 As the obtaining of Mössbauer spectrum require the gamma ray source with high energy at low temperature, the further application of Mössbauer spectrum is greatly limited.

⁵⁷Fe Mössbauer spectroscopy conducting at cryogenic temperatures (8 K) can prevent signal loss caused by recoil of mobile species, and are proved to be more accurate than UV-vis and H2-TPR in quantification of Fe species in zeolites.68 According to previous studies, 13,23,24,68 four key parameters, *i.e.* average center shift (CS, mm s⁻¹), average quadrupole splitting (QS, mm s⁻¹), standard deviation of QS (ε , mm s⁻¹) and average magnetic hyperfine field (HF, Tesla) could be used to distinguish different Fe species in the Mössbauer spectroscopy of Fe/ SSZ-13 zeolites.57 Generally, the component with a CS value of \sim 1.4 mm s⁻¹ is attributed to Fe(II) species, while those with CS value of ~ 0.5 mm s⁻¹ can be assigned to Fe(III) species. Also, the paramagnetic Fe species give doublet features in Mössbauer spectroscopy (designated as P), while the magnetic Fe species display sextet signals (designated as M).13,23,24,68 Based on above features, the Fe species in Fe/SSZ-13 zeolites can be distinguished and divided into three types:13 Fe(III)-P representing Fe³⁺ dimers (HO-Fe(III)-O-Fe(III)-OH), Fe(II)-P assigning to isolated Fe^{2+} species, and Fe(m)-M to a mixture of isolated Fe^{3+} species ($[Fe(OH)_2]^+$) and Fe-oxide clusters/particles. By spectra deconvolution, the relative percentages of three types of Fe species in Fa/SSZ-13 zeolites can be estimated, as shown in Fig. 5, according to Gao and co-workers.13

Based on the quantification of ⁵⁷Fe Mössbauer spectroscopy and kinetic experiments, Gao and co-workers13 had detailly investigated the active Fe sites in NH3-SCR reactions over a series of Fe/SSZ-13 zeolites with differentiate iron contents. They found that the isolated Fe^{3+} species were the main active sites for standard NH₃-SCR at low temperatures (≤ 260 °C), while the [HO-Fe-O-Fe-OH]²⁺ species dominated the NH₃-SCR reactions in the high temperature range (260-550 °C). Moreover, the migration and aggregation of Fe species in Fe/SSZ-13 zeolites during the hydrothermal aging treatments had also been clearly clarified by 57Fe Mössbauer spectroscopy:24 the isolated Fe³⁺ species would gradually transform to [HO-Fe-O-Fe–OH $^{2+}$ under mild hydrothermal conditions (600–700 °C), which was beneficial for the enhancement of NH₃-SCR activity. However, once the hydrothermal aging temperature exceeding 800 °C, the NH₃-SCR activity of aged Fe/SSZ-13 zeolites dramatically decreased due to serious framework dealumination, accompanying by the agglomeration of active isolated Fe³⁺ species to Fe_xO_y clusters or nanoparticles (without or with very low NH₃-SCR activity) and even the incorporation of Al into Fe_xO_y species (almost no SCR activity).

As the intensity of the Mössbauer signal is strongly temperature dependent (usually, the ultra-low testing temperature of 8 K is required for high resolution), the quantitative determination of the oxidation of Fe species in zeolites by in situ Mössbauer spectroscopy is not possible under real NH₃-SCR reactions at elevated temperatures.145 However, Maier et al.107 has developed an effective method to quantitative determining the oxidation state of Fe species in Fe/Bata zeolites under real NH3-SCR conditions by combining in situ XANES and Mössbauer spectroscopy. They had obtained a linear correlation between the edge energy of the XANES and the oxidation state determined by Mössbauer spectroscopy, which in turn allowed them to determining the relative concentrations of Fe³⁺ and Fe²⁺ species under real NH₃-SCR conditions through in situ XANES with the aid of Mössbauer spectroscopy. In conclusion, the application and determination of Fe species in zeolites for NH₃-SCR are summarized in Fig. 6.

Compared with UV-vis, H2-TPR and EPR experiments, Mössbauer spectroscopy is the most accurate method for the simultaneously determination of both Fe²⁺ and Fe³⁺ species in zeolites with high resolution and sensitivity.^{13,24} In addition, only several type of nucleuses (57Fe and 119Sn) have the resonance absorption of Mössbauer effect, the determination of Mössbauer spectroscopy is not disturbed by other elements, which guarantees the high accuracy of Mössbauer spectroscopy but also limits its application. Moreover, the high cost of equipment with γ -ray sources and the low testing temperature (8 K) for high resolution also limit its application.¹⁴³

Review

Table 8 The summarized applications and limitations of different characterization methods on the detecting of Fe and Cu species in zeolites for NH₃-SCR

Characterization methods	Fe species	Cu species	Limitation
UV-vis	(1) 200–300 nm: 220–250 nm belongs to the four-coordinated isolated Fe^{3+} species, 250–300 nm are related to isolated Fe^{3+} species with higher coordination number	(1) 210 and 280 nm: isolated Cu^{2+} species (charge transfer from lattice O^{2-} to Cu^{2+})	(1) Only Fe^{3+} and Cu^{2+} species can be detected, Fe^{2+} and Cu^+ species are invisible in 200–800 nm of UV- vis spectra ^{62–64,66}
	(2) 300–400 nm: charge transition peak of octahedral coordination aggregated Fe^{3+} species such as small Fe_xO_y species	(2) <i>ca.</i> 750 nm: isolated Cu^{2+} species (d-d transitions of Cu^{2+} species with distorted octahedral coordination) ⁶¹⁻⁶⁴	(2) Only a semiquantitative method due to the unknown extinction coefficients of different adsorption band of various metal species ^{59,66}
	(3) >400 nm: Fe ₂ O ₃ nanoparticles ^{34,59,60}	(3) 250 nm and 450 nm: CuO_x species (the charge transfer (250 nm) and d–d transition (450 nm) of octahedral coordinated Cu^{2+} in CuO_x species ^{25,61,62,65}	(3) Only the coordination state of metal species can be obtained, the detailed chemical structure of metal species cannot be determined ^{64,67}
H ₂ -TPR	(1) 380–430 °C: the reduction of isolated Fe^{3+} to Fe^{2+} species ^{24,69,70}	(1) 400 °C: the reduction of Cu^{2+} -2Z to Cu^{+} species	(1) Unable to determine irreducible metal species such as Cu^0 and Fe^0 in zeolites
	(2) 500–560 °C: the reduction of aggregated Fe_xO_y species ^{24,69,70}	(2) The reduction of $[Cu(OH)]^+$ -Z to Cu ⁺ at 250 °C, then Cu ⁺ to Cu ⁰ at 360 °C (ref. 27, 74 and 77)	(2) The distinguish of reduction peak for various metal species are difficult as they may shift and overlap with each other ³⁵
	(3) 680–750 °C: the reduction of Fe_2O_3 nanoparticles ⁶⁹	(3) 300 °C: the reduction of CuO to Cu^0 species ^{27,29,74}	(3) The assignment of reduction peak should consider the zeolite support, metal content, preparation method of catalysts ^{62,75,78,80}
	(4) 900–1000 °C: the reduction of Fe^{2+} species in ion-exchange sites and high aggregated Fe_2O_3 or Fe_3O_4 particles ^{34,69,71–73}	(4) 700–900 °C: Cu^+ at the ion- exchange site of zeolite be reduced to Cu^0 species ^{27,29}	 (4) The automatic reduction of metal species in the dehydration pre-treatment process caused by adsorbed H₂O in zeolites may decrease the H₂ consumption^{77,81} (5) The shape and area of reduction peak in the H₂-TPR experiments could be affected by the heating rate of temperature-programmed process⁸²
XPS	(1) $\text{Fe}^{2+} 2p_{3/2}$ and $2p_{1/2}$ signals are those located at binding energy of <i>ca.</i> 710 eV and 723 eV with satellite peaks at <i>ca.</i> 715 eV and 729 eV, respectively ^{74,84,92-94}	(1) Cu $2p_{1/2}$ peak splits into two signals at 952.3 \pm 0.2 eV for Cu ⁺ and at 953.6 \pm 0.2 eV for Cu ²⁺ species ^{84,85}	(1) Only elements with nano-scale thickness on the surface of zeolites can be detected ^{84,97,98}
	(2) $\operatorname{Fe}^{3+} 2p_{3/2}$ and $2p_{1/2}$ signals are those located at about 711 eV and 724 eV with satellite peaks at <i>ca</i> . 719 eV and 733 eV, respectively ^{92,96}	(2) The assignment of Cu $2p_{3/2}$ signals are controversial. Some researchers attributed the Cu $2p_{3/2}$ signals at 932.5 \pm 0.2 eV for Cu ⁺ and those at 933.7 \pm 0.2 eV for Cu ²⁺ species, ⁸⁴⁻⁸⁶ while others attributing them to CuO species and isolated Cu ²⁺ species, respectively ⁸⁷	 (2) The automatic reduction of Cu²⁺ or Fe³⁺ species under pretreatment conditions of ultra-high vacuum⁹⁹ (3) The assignment of XPS peak are sometimes difficult due to shift and overlapping of binding energy signals for metal species,^{89,96} better be carefully taken and with the aid of ICP-AES, EPR, Auger electron energy signates and UV uie spectro^{88-92,94,95}
XAFS	(1) Distinguish and quantification of Fe ²⁺ and Fe ³⁺ species in Fe/ zeolites ¹⁰⁷	(1) Distinguish and quantification of Cu ⁺ and Cu ²⁺ species in Cu/ zeolites ^{28,105}	(1) The signals of all absorbing atoms of one type in the sample may overlap at the edge, which made it difficult to distinguish different kind of species ¹⁰²
	(2) Obtain the local structure of Fe species such as coordination number and bond lengths for Fe–O and Fe–Fe coordination spheres ¹⁰⁸	(2) Obtain the local structure of Cu species such as coordination number and bond lengths for Cu–O and Cu–Cu coordination spheres ^{25,26}	(2) The accessibility of synchrotrons of X-ray is not easy, as beam times are scarce and need to be scheduled months ahead ¹⁰⁴

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Table 8 (Contd.)

Characterization methods	Fe species	Cu species	Limitation
	(3) <i>Operando</i> XAS can be used to monitor the oxidation and reduction half-cycle of Fe species in real NH ₃ -SCR reaction conditions ¹⁰⁹	(3) <i>Operando</i> XAS can be used to monitor the oxidation and reduction half-cycle of Cu species under real NH ₃ -SCR reaction conditions ^{28,32,105,106}	
FTIR spectroscopy	(1) FTIR of adsorption CO: selectively detecting Fe^{2+} species by weak adsorption to form Fe^{2+} -CO species, while Fe^{3+} -OH could coordinated with CO to form Fe^{3+} - OH…CO species ^{58,122,126}	(1) FTIR of adsorption CO: selectively detecting Cu^+ species by forming Cu^+ -CO, Cu^+ -(CO) ₂ species; Cu^{2+} -CO can only be formed under excessive CO condition ¹²⁷⁻¹²⁹	(1) The automatic reduction of Cu ²⁺ or Fe ³⁺ species under pretreatment conditions of ultra-high vacuum ^{115,123,124}
	(2) FTIR of adsorption NO: selectively detecting Fe^{2+} species by strong adsorption to form Fe^{2+} -NO, Fe^{2+} -(NO) ₂ and Fe^{2+} -(NO) ₃ species ^{24,125}	(2) FTIR of adsorption NO: both Cu ⁺ and Cu ²⁺ species can be detected by strong adsorption to form Cu ²⁺ –NO, Cu ⁺ –NO, Cu ⁺ –(NO) ₂ complexes; $[Cu(OH)]^+$ and $[Cu–O-Cu]^{2+}$ can also coordinated with NO to form IR signal ^{127,129,130}	 (2) The assignment of IR bands should be careful due to shifting and overlapping of signals for metal species when catalysts with high metal content or complex composition^{1,7,14,79,115,127,129} (3) Only a semiquantitative method due to the unknown extinction
EPR	(1) EPR silent: Fe ²⁺ species ¹³	(1) EPR silent: Cu ⁺ , [Cu(OH)] ⁺ , CuO _x and [Cu–O–Cu] ²⁺ species ²⁷	coefficients of different adsorption band of various metal species ¹⁴⁸ (1) Low testing temperature (155 K for Cu-based zeolites and 7 K for Fe- based zeolites) is required for taking high-resolution EPR spectra so as to relieve the peak broadening
	(2) EPR active: Fe^{3+} species, including framework, extra- framework Fe^{3+} in zeolites and Fe^{3+} in Fe O. clustere ^{73,141,142}	(2) EPR active: isolated Cu^{2+} , $[Cu(H_2O)_6]^{2+}$ and $[Cu(OH)(H_2O)_5]^+$ species ^{27,77}	resulting from metal mobility and antiferromagnetic interactions ^{24,78} (2) High sensitivity of EPR signal to H ₂ O and paramagnetic species ²¹
	In re _x O _y clusters	 (3) The quantitative measuring of different Cu species in Cu/SSZ-13 can be achieved by combining EPR and ICP-AES method²⁷ (4) The Cu-Cu distance of isolated Cu²⁺ ions in Cu/SSZ-13 can be estimated by the line broadening of TRACE and T	(3) The deviation of <i>g</i> values for metal species with different zeolite supports made the assignments of EPR signal difficult ¹⁰⁹
Mössbauer spectroscopy	(1) Determination of Fe^{2+} and Fe^{3+} at the same time	Unavailable	(1) Only applicable to several nucleus with Mossbauer effect, such as ⁵⁷ Fe and ¹¹⁹ Sp ¹⁴³
	(2) Distinguishing of different types of Fe species: Fe(m)-P representing Fe ³⁺ dimers (HO–Fe(m)–O–Fe(m)– OH)), Fe(n)-P assigning to isolated Fe ²⁺ species, and Fe(m)-M to a mixture of isolated Fe ³⁺ species		 (2) Super-low testing temperature (8 K) for high resolution^{13,24,68} (3) High cost of equipment with γ-ray sources which are not easy to be available¹⁴³
	([Fe(OH) ₂]') and Fe-oxide clusters/ particles ^{13,23,24,68}		
DFT	(1) Verify the spectral results of gas mo	olecules adsorption (CO, NO, <i>etc.</i>) ^{124,127}	(1) Calculation results may deviate from the actual structures due to the saturation of the boundary of the cluster model with hydrogen atoms ⁵⁶
	(2) Determining the location and dist catalysts ^{146,147}	ribution of active sites on the	(2) Zeolite with complex spatial structures would result in huge calculations and the loss of accuracy of calculation results sometimes ⁵⁶

Characterization methods	Fe species	Cu species	Limitation
	(3) Calculating the activa rate-determining step fo	tion energy of the elementary reaction to reveal the r $\rm NH_3\text{-}SCR^{146,147}$	(3) Calculation results of some special systems were heavily dependent on the selection of calculation methods ⁵⁶
	(4) Determining the read species and transition st	tion pathway by calculating the intermediates ate energy of NH_3 -SCR reactions, <i>etc.</i> ^{28,32,56}	

2.8 DFT calculation

The density functional theory (DFT) calculation is another powerful tool to study the chemical state of metal species, the key reaction intermediates and the reaction mechanism of NH₃-SCR, which could be used to study the interactions between atoms or molecules with the catalysts from atomic-scale.

As a gas-solid multiphase reaction, the gas molecules adsorption process is important for the study of NH₃-SCR mechanism, which is usually investigated by experimental method such as FTIR spectra, XAFS, and reaction kinetics. DFT can be used to predict and verify the spectral results of gas molecules adsorption (CO, NO, N2, NH3, etc.) so as to investigate the key metal species and reaction mechanism of NH₃-SCR. Zhang et al.124 had investigated the NO adsorption process over Cu-SSZ-13 zeolite by FTIR spectra and DFT calculations and found a perfect agreement between FTIR bands and DFT calculation results for the NO vibration frequencies, as shown in Table 7. Base on FTIR results and DFT calculations, they concluded that NO molecules did bind stronger on [Cu(OH)]⁺ located in 8MR than isolated Cu²⁺ species in the 6MR of CHA structure in Cu/SSZ-13 zeolites, which indicated that Cu²⁺ ions were stabilized with ligands in 8MR of CHA cages in NH₃-SCR. Similarly, Corma et al.127 had also clearly identified different kinds of Cu-NO complexes in Cu/SAPO-34 and Cu/SSZ-13 zeolites by combining FTIR spectra of NO adsorption and DFT calculations, which could be used to indirectly determining the distribution of Cu species in zeolites.

DFT can also be used to determine the distribution and spatial location of metal active sites, the key intermediate species and to reaction pathway in NH₃-SCR. Li et al.¹⁴⁶ had explored the possible locations of Cu²⁺ species in Cu/SAPO-18 by DFT calculations and EPR experiments. They calculated and found two of seven possible locations of Cu2+ species were the most stable energy state, and then revealed the NH₃-SCR reaction mechanism over Cu/SAPO-18 based on that. Mao et al.¹⁴⁷ calculated the binding energy of Cu²⁺ species on five type of ion exchange sites in SAPO-34 and found that Cu²⁺ species located in the 6MR plane with slightly off-center position had the lowest binding energy, which were the most stable exchange sites for Cu²⁺ in SAPO-34. Further research indicated that those stable Cu²⁺ species were the main active sites for Cu/ SAPO-34 zeolites in NH₃-SCR.

McEwen et al.28 investigated the oxidation state and coordination environment of Cu species in Cu/SSZ-13 under standard SCR or rapid SCR conditions by operando XAS with the aid of DFT calculations. They found that the oxidation state of Cu species changed with reaction conditions: four-foldcoordinated Cu2+ species dominated the Cu/SSZ-13 zeolites under fast and slow SCR conditions, in which the NO₂/NO_r ratios were 0.5 and 1 in the feed gas, respectively. In contrast, mixed Cu⁺ and Cu²⁺ oxidation states were observed under standard SCR conditions without NO₂ in the feed gas, which indicated a reduction in the average Cu coordination and highlighted the role of Cu redox chemistry in NH₃-SCR process. Based on DFT calculation and kinetic experiments, Gao et al.32 studied the oxidation half-cycle of Cu⁺ to Cu²⁺ process over Cu/ SSZ-13 in NH₃-SCR and found that the isolated Cu⁺ species were unable to complete oxidation half-cycle at low temperatures, which process could only occur with the participation of two isolated Cu^+ ions by forming $[Cu^{I}(NH_3)_2]^+ - O_2 - [Cu^{I}(NH_3)_2]^+$ intermediates. In addition, the above oxidation half-cycle was the rate-determining step for NH₃-SCR at low temperatures, which was confirmed by DFT calculations.

Recently, Guan et al.⁵⁶ reviewed the application of DFT in NH₃-SCR research from the aspects of surface adsorption, metal active sites characteristics, reaction mechanism, hydrothermal aging mechanism and poisoning mechanism in catalysts. DFT calculations can obtain a lot of information of catalysts in NH3-SCR, which can not only verify the experimental characterization results to make them more reliable, but also reveal the underlying causes of experimental results from microscopic atomic level. The current use of DFT in NH3-SCR included: determining the location and distribution of active sites on the catalysts, calculating the activation energy of the elementary reaction to reveal the rate-determining step for NH₃-SCR, determining the reaction pathway by calculating the intermediates species and transition state energy of NH₃-SCR reactions, etc.

Though DFT is a universal method to investigate the physicochemical and reactivity properties of catalysts which is not restricted by the research project or the research process, there are still shortcomings. Firstly, when constructing models, saturation of the boundary of the cluster model with hydrogen atoms may cause deviations from the actual structures. Secondly, zeolite with complex spatial structures would result in huge calculations and the loss of accuracy of calculation results sometimes. Thirdly, the DFT calculation results of some special systems were heavily dependent on the selection of calculation methods. However, the development of calculation software and methods may help to solve those problem. By combining

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with advanced experimental methods, DFT calculation has become one of the most important tool to investigate the reaction mechanism of NH₃-SCR.

3 Conclusions and outlook

Cu-based and Fe-based zeolites are promising catalysts for NH₃-SCR due to the high catalytic activity, wide temperature window and good hydrothermal stability. The detailed investigation of NH₃-SCR mechanism based on Cu-based and Fe-based zeolites are important for further development of high-efficiency NH₃-SCR catalysts, which should be based on the accurate determining of active metal sites. Fig. 7 summarizing the effective characterization methods of various Cu or Fe species in zeolites for NH₃-SCR. As also summarized in Table 8, UV-vis, H₂-TPR, XPS, XAFS, FTIR (adsorption of CO or NO), EPR, Mössbauer spectroscopy and DFT calculations introduced in this review are characteristic methods to determine the type, content, distribution or even local structure of various Cu or Fe species in zeolites, though they have different applicability and limitations. In addition, the accurate qualitative and quantitative determination of various metal active sites in Cu-based or Febased zeolites usually requires a combination of several characterization methods by considering the preparation method of catalysts and by careful analyzing the characterization results. Moreover, off-line characterization methods often cannot precisely reveal the chemical environment of metal active species in real NH₃-SCR conditions, as well as the interactions between active sites with reactants. Therefore, the in situ or operando characterization methods such as in situ IR, in situ UVvis, in situ EPR, operando XAFS, etc., as well as DFT calculations should also be applied to more accurately reveal the activation and reaction process of active species on the catalysts so as to reveal the detailed reaction mechanism of NH₃-SCR.

Author contributions

Jialing Chen: conception, investigation and writing-review & editing; Wei Huang: investigation and methodology; Sizhuo Bao: investigation and methodology; Wenbo Zhang: investigation and methodology; Tingyu Liang: methodology, and review & editing; Shenke Zheng: IR spectroscopy analysis; Lan Yi: UV-vis analysis; Li Guo: H_2 -TPR analysis; Xiaoqin Wu: review & editing. All authors have read and agreed to the published version of the manuscript.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

This article is devoted to the 60th birthday of our beloved Prof. Jianguo Wang (Shanxi Institute of Coal Chemistry, University of Chinese Academy of Sciences). We are grateful for the financial supports of the National Natural Science Foundation of China (22002114 and 22102124), the National Innovation and Entrepreneurship Training Program for College Students (201810488016); the Education Department of Hubei Province (Q20211501), the Open Fund of Key Laboratory of Hubei Province for Coal Conversion and New Carbon Materials (WKDM202208). We would like to thank Mr Guohong Zhang, Jinhui Zhou and Feizhou Wang at the Analytical & Testing Center of Wuhan University of Science and Technology for the help on XPS and FTIR experimental method.

References

- 1 U. Deka, I. Lezcano-Gonzalez, B. M. Weckhuysen and A. M. Beale, *ACS Catal.*, 2013, 3, 413–427.
- 2 L. Han, S. Cai, M. Gao, J.-y. Hasegawa, P. Wang, J. Zhang,
 L. Shi and D. Zhang, *Chem. Rev.*, 2019, 119, 10916–10976.
- 3 L. Zhang, Q. Wu, X. Meng, U. Müller, M. Feyen, D. Dai,
 S. Maurer, R. McGuire, A. Moini, A.-N. Parvulescu,
 W. Zhang, C. Shi, T. Yokoi, X. Pan, X. Bao, H. Gies,
 B. Marler, D. E. De Vos, U. Kolb and F.-S. Xiao, *React. Chem. Eng.*, 2019, 4, 975–985.
- 4 F. Liu, Y. Yu and H. He, Chem. Commun., 2014, 45, 8445-8463.
- 5 Y. Yue, B. Liu, P. Qin, N. Lv, T. Wang, X. Bi, H. Zhu, P. Yuan,
 Z. Bai, Q. Cui and X. Bao, *Chem. Eng. J.*, 2020, **398**, 125515–125527.
- 6 A. M. Beale, I. Lezcano-Gonzalez, T. Maunula and R. G. Palgrave, *Catal., Struct. React.*, 2015, 1, 25–34.
- 7 T. Jiang and R. F. Lobo, in *Structure and Reactivity of Metals in Zeolite Materials*, ed. J. Pérez Pariente and M. Sánchez-Sánchez, Springer International Publishing, Cham, 2018, DOI: 10.1007/430_2018_23, pp. 155–178.
- 8 J. Wang, H. Zhao, G. Haller and Y. Li, *Appl. Catal., B*, 2017, **202**, 346–354.
- 9 C. Paolucci, J. R. Di Iorio, F. H. Ribeiro, R. Gounder and W. F. Schneider, in *Advances in Catalysis*, ed. C. Song, 2016, vol. 59, pp. 1–107.
- 10 R. Zhang, N. Liu, Z. Lei and B. Chen, *Chem. Rev.*, 2016, **116**, 3658–3721.
- 11 T. J. Toops, J. A. Pihl and W. P. Partridge, in Urea-SCR Technology for deNOx After Treatment of Diesel Exhausts, ed. I. Nova and E. Tronconi, Springer New York, New York, 2014, DOI: 10.1007/978-1-4899-8071-7_4, pp. 97–121.
- 12 F. Gao, E. D. Walter, M. Kollar, Y. Wang, J. Szanyi and C. H. F. Peden, *J. Catal.*, 2014, **319**, 1–14.
- F. Gao, Y. Zheng, R. K. Kukkadapu, Y. L. Wang, E. D. Walter, B. Schwenzer, J. Szanyi and C. H. F. Peden, *ACS Catal.*, 2016, 6, 2939–2954.
- 14 F. Gao, ChemCatChem, 2020, 10, 1324.
- 15 Y. Shan, J. Du, Y. Zhang, W. Shan, X. Shi, Y. Yu, R. Zhang,
 X. Meng, F. S. Xiao and H. He, *Natl. Sci. Rev.*, 2021, 8, 134–153.
- 16 A. M. Beale, F. Gao, I. Lezcano-Gonzalez, C. H. Peden and J. Szanyi, *Chem. Soc. Rev.*, 2015, 44, 7371–7405.
- 17 A. Wang, Y. Chen, E. D. Walter, N. M. Washton, D. Mei, T. Varga, Y. Wang, J. Szanyi, Y. Wang, C. H. F. Peden and F. Gao, *Nat. Commun.*, 2019, **10**, 1137–1147.

- 18 W. Zhang, J. Chen, L. Guo, W. Zheng, G. Wang, S. Zheng and X. Wu, J. Fuel Chem. Technol., 2021, 49, 1294-1315.
- 19 W. Zheng, J. Chen, L. Guo, W. Zhang, H. Zhao and X. Wu, J. Fuel Chem. Technol., 2020, 48, 1193-1210.
- 20 Y. Zhang, J. Zhang, H. Wang, W. Yang, C. Wang, Y. Peng, J. Chen, J. Li and F. Gao, J. Phys. Chem. C, 2022, 126, 8720-8733.
- 21 Y. Wu, Y. Ma, Y. Wang, K. G. Rappé, N. M. Washton, Y. Wang, E. D. Walter and F. Gao, J. Am. Chem. Soc., 2022, 144, 9734-9746.
- 22 Y. Zhang, Y. Peng, J. Li, K. Groden, J.-S. McEwen, E. D. Walter, Y. Chen, Y. Wang and F. Gao, ACS Catal., 2020, 10, 9410-9419.
- 23 F. Gao, M. Kollár, R. K. Kukkadapu, N. M. Washton, Y. Wang, J. Szanvi and C. H. Peden, Appl. Catal., B, 2015, 164, 407-419.
- 24 L. Kovarik, N. M. Washton, R. K. Kukkadapu, A. Devaraj, A. Wang, Y. Wang, J. Szanyi, C. H. F. Peden and F. Gao, ACS Catal., 2017, 7, 2458-2470.
- 25 S. T. Korhonen, D. W. Fickel, R. F. Lobo, B. M. Weckhuysen and A. M. Beale, Chem. Commun., 2011, 47, 800-802.
- 26 U. Deka, A. Juhin, E. A. Eilertsen, H. Emerich, M. A. Green, S. T. Korhonen, B. M. Weckhuysen and A. M. Beale, J. Phys. Chem. C, 2012, 116, 4809-4818.
- 27 J. Song, Y. L. Wang, E. D. Walter, N. M. Washton, D. H. Mei, L. Kovarik, M. H. Engelhard, S. Prodinger, Y. Wang, C. H. F. Peden and F. Gao, ACS Catal., 2017, 7, 8214-8227.
- 28 J. S. McEwen, T. Anggara, W. F. Schneider, V. F. Kispersky, J. T. Miller, W. N. Delgass and F. H. Ribeiro, Catal. Today, 2012, 184, 129-144.
- 29 J. Xue, X. Wang, G. Qi, J. Wang, M. Shen and W. Li, J. Catal., 2013, 297, 56-64.
- 30 C. Paolucci, A. A. Parekh, I. Khurana, J. R. Di Iorio, H. Li, J. D. A. Caballero, A. J. Shih, T. Anggara, W. N. Delgass, J. T. Miller, F. H. Ribeiro, R. Gounder and W. F. Schneider, J. Am. Chem. Soc., 2016, 138, 6028-6048.
- 31 B. Chen, R. Xu, R. Zhang and N. Liu, Environ. Sci. Technol., 2014, 48, 13909-13916.
- 32 F. Gao, D. Mei, Y. Wang, J. Szanyi and C. H. F. Peden, J. Am. Chem. Soc., 2017, 139, 4935-4942.
- 33 S. Zhao, L. Huang, B. Jiang, M. Cheng, J. Zhang and Y. Hu, Chin. J. Catal., 2018, 39, 800-809.
- 34 J. Chen, G. Peng, W. Zheng, W. Zhang, L. Guo and X. Wu, Catal. Sci. Technol., 2020, 10, 6583-6598.
- 35 J. Chen, G. Peng, T. Liang, W. Zhang, W. Zheng, H. Zhao, L. Guo and X. Wu, Nanomaterials, 2020, 10, 2170.
- 36 S. Mohan, P. Dinesha and S. Kumar, Chem. Eng. J., 2020, 384, 123253-123262.
- 37 M. Jabłońska, Mol. Catal., 2022, 518, 112111.
- 38 H. Lei, V. Rizzotto, A. Guo, D. Ye, U. Simon and P. Chen, Catalysts, 2021, 11, 52.
- 39 S. Zhang, L. Pang, Z. Chen, S. Ming, Y. Dong, Q. Liu, P. Liu, W. Cai and T. Li, Appl. Catal., A, 2020, 607, 117855.
- 40 C. H. F. Peden, J. Catal., 2019, 373, 384-389.
- 41 Q. Liu, C. Bian, S. Ming, L. Guo, S. Zhang, L. Pang, P. Liu, Z. Chen and T. Li, Appl. Catal., A, 2020, 607, 117865.

- 42 Y. Pu, X. Xie, W. Jiang, L. Yang, X. Jiang and L. Yao, Chin. Chem. Lett., 2020, 31, 2549-2555.
- 43 T. Andana, K. G. Rappé, F. Gao, J. Szanyi, X. Pereira-Hernandez and Y. Wang, Appl. Catal., B, 2021, 291, 120054.
- 44 Z. Zhang, J. Li, J. Tian, Y. Zhong, Z. Zou, R. Dong, S. Gao, W. Xu and D. Tan, Fuel Process. Technol., 2022, 230, 107213.
- 45 J. Yang, Y. Huang, J. Su, L. Chen, M. Zhang, M. Gao, M. Yang, F. Wang, X. Zhang and B. Shen, Sep. Purif. Technol., 2022, 297, 121544.
- 46 R. T. Guo, B. Qin, L. G. Wei, T. Y. Yin, J. Zhou and W. G. Pan, Phys. Chem. Chem. Phys., 2022, 24, 363-6382.
- 47 N. Zhang, H. He, D. Wang and Y. Li, J. Solid State Chem., 2020, 289, 121464.
- 48 M. Cai, X. Bian, F. Xie, W. Wu and P. Cen, Catalysts, 2021, 11, 361.
- 49 W. Shan, Y. Yu, Y. Zhang, G. He and H. He, Catal. Today, 2020, 376, 292-301.
- 50 S. J. Park, Catalysts, 2021, 11, 1519.
- 51 Z. Lian, Y. Li, W. Shan and H. He, Catalysts, 2020, 10, 1421.
- 52 C. Liu, H. Wang, Z. Zhang and Q. Liu, Catalysts, 2020, 10, 1034.
- 53 J. Xu, Y. Zhang, X. Zou, T. Tang, Q. Zhang, F. Guo and H. Liu, New J. Chem., 2022, 46, 2053-2067.
- 54 G. Xu, X. Guo, X. Cheng, J. Yu and B. Fang, Nanoscale, 2021, 13, 7052-7080.
- 55 K. Guo, J. Ji, W. Song, J. Sun, C. Tang and L. Dong, Appl. Catal., B, 2021, 297, 120388.
- 56 B. Guan, H. Jiang, Y. Wei, Z. Liu, X. Wu, H. Lin and Z. Huang, Mol. Catal., 2021, 510, 111704.
- 57 M. Li, Y. Guo and J. Yang, ChemCatChem, 2020, 19, 5599-5610.
- 58 J. Kim, A. Jentys, S. M. Maier and J. A. Lercher, J. Phys. Chem. C, 2013, 117, 986-993.
- 59 J. Pérez-Ramírez, J. Groen, A. Brückner, M. S. Kumar, U. Bentrup, M. Debbagh and L. Villaescusa, J. Catal., 2005, 232, 318-334.
- 60 R. Nedyalkova, S. Shwan, M. Skoglundh and L. Olsson, Appl. Catal., B, 2013, 138-139, 373-380.
- 61 H. Praliaud, S. Mikhailenko, Z. Chajar and M. Primet, Appl. Catal., B, 1998, 16, 359-374.
- 62 Z. Zhao, R. Yu, R. Zhao, C. Shi, H. Gies, F. S. Xiao, D. D. Vos, T. Yokoi, X. Bao and U. Kolb, Appl. Catal., B, 2017, 217, 421-428.
- 63 A. El-Trass, H. ElShamy, I. El-Mehasseb and M. El-Kemary, Appl. Surf. Sci., 2012, 258, 2997-3001.
- 64 M. H. Groothaert, J. A. van Bokhoven, A. A. Battiston, B. M. Weckhuysen and R. A. Schoonheydt, J. Am. Chem. Soc., 2003, 125, 7629-7640.
- 65 I. Lezcano-Gonzalez, U. Deka, H. E. V. D. Bij, P. Paalanen, B. Arstad, B. M. Weckhuysen and A. M. Beale, Appl. Catal., B, 2014, 154-155, 339-349.
- 66 J. Pérez-Ramírez, M. Santhosh Kumar and A. Brückner, J. Catal., 2004, 223, 13-27.
- 67 B. Ipek, M. J. Wulfers, H. Kim, F. Goltl, I. Hermans, J. P. Smith, K. S. Booksh, C. M. Brown and R. F. Lobo, ACS Catal., 2017, 7, 4291-4303.

Review

- 68 A. Wang, Y. Wang, E. D. Walter, R. K. Kukkadapu, Y. Guo,
 G. Lu, R. S. Weber, Y. Wang, C. H. F. Peden and F. Gao, *J. Catal.*, 2018, 358, 199–210.
- 69 S. Brandenberger, O. Kröcher, M. Casapu, A. Tissler and R. Althoff, *Appl. Catal.*, *B*, 2011, **101**, 649–659.
- 70 K. Niu, G. Li, J. Liu and Y. Wei, *J. Solid State Chem.*, 2020, 287, 121330–1213336.
- 71 X. Shi, H. He and L. Xie, Chin. J. Catal., 2015, 36, 649-656.
- 72 K. Krishna, G. B. F. Seijger, C. M. V. D. Bleek, M. Makkee and H. P. A. Calis, *Catal. Lett.*, 2003, **86**, 121–132.
- 73 E. Yuan, G. Wu, W. Dai, N. Guan and L. Li, *Catal. Sci. Technol.*, 2017, 7, 3036–3044.
- 74 J. H. Kwak, H. Zhu, J. H. Lee, C. H. Peden and J. Szanyi, *Chem. Commun.*, 2012, **48**, 4758–4760.
- 75 H. Wang, R. Xu, Y. Jin and R. Zhang, *Catal. Today*, 2019, 327, 295–307.
- 76 Y. Cui, Y. Wang, E. D. Walter, J. Szanyi, Y. Wang and F. Gao, *Catal. Today*, 2019, **339**, 233–240.
- 77 F. Gao, N. M. Washton, Y. Wang, M. Kollár, J. Szanyi and C. H. F. Peden, *J. Catal.*, 2015, 331, 25–38.
- 78 F. Gao, E. D. Walter, E. M. Karp, J. Luo, R. G. Tonkyn, J. H. Kwak, J. Szanyi and C. H. F. Peden, *J. Catal.*, 2013, 300, 20–29.
- 79 F. Lin, T. Andana, Y. Wu, J. Szanyi, Y. Wang and F. Gao, *J. Catal.*, 2021, **401**, 70–80.
- 80 J. Li, N. Wilken, K. Kamasamudram and N. W. Currier, *Top. Catal.*, 2013, **56**, 201–204.
- 81 F. Gao, J. H. Kwak, J. Szanyi and C. H. F. Peden, *Top. Catal.*, 2013, **56**, 1441–1459.
- 82 J. M. Kanervo and A. O. I. Krause, J. Catal., 2002, 207, 57-65.
- 83 J. H. Lee, Y. J. Kim, T. Ryu, P. S. Kim, H. K. Chang and S. B. Hong, *Appl. Catal.*, *B*, 2017, **200**, 428–438.
- 84 Q. Ye, L. Wang and R. T. Yang, *Appl. Catal.*, *A*, 2012, 427, 24–34.
- 85 J. Chastain and R. C. King Jr, *Handbook of X-ray photoelectron spectroscopy*, J Perkin-Elmer Corporation, 1992.
- 86 L. Xu, C. Shi, B. B. Chen, Q. Zhao, Y. J. Zhu, H. Gies, F. S. Xiao, D. De Vos, T. Yokoi, X. H. Bao, U. Kolb, M. Feyen, S. Maurer, A. Moini, U. Muller and W. P. Zhang, *Microporous Mesoporous Mater.*, 2016, 236, 211–217.
- 87 H. Jiang, B. Guan, H. Lin and Z. Huang, *Fuel*, 2019, 255, 115587.
- 88 H. Yang, X. Cui, S. Li, Y. Cen, T. Deng, J. Wang, U. Olsbye and W. Fan, *Microporous Mesoporous Mater.*, 2020, 305, 110381.
- 89 H. Yang, Y. Chen, X. Cui, G. Wang, Y. Cen, T. Deng, W. Yan, J. Gao, S. Zhu and U. Olsbye, *Angew. Chem., Int. Ed.*, 2018, 130, 1854–1858.
- 90 J. Gong, H. Yue, Y. Zhao, S. Zhao, L. Zhao, J. Lv, S. Wang and X. Ma, J. Am. Chem. Soc., 2012, 134, 13922–13925.
- 91 S. Velu, K. Suzuki, M. Vijayaraj, S. Barman and C. S. Gopinath, *Appl. Catal.*, *B*, 2005, 55, 287–299.
- 92 F. Mercier, N. Thromat and C. Beaucaire, *Appl. Surf. Sci.*, 2000, **165**, 2880302.

- 93 J. Gurgul, K. Łątka, I. Hnat, J. Rynkowski and S. Dzwigaj, *Microporous Mesoporous Mater.*, 2013, **168**, 1–6.
- 94 T. Yamashita and P. Hayes, *Appl. Surf. Sci.*, 2008, **254**, 2441–2449.
- 95 D. D. Hawn and B. M. DeKoven, Surf. Interface Anal., 1987, 10, 63–74.
- 96 P. Boron, L. Chmielarz, J. Gurgul, K. Łatka, B. Gil,
 B. Marszałek and S. Dzwigaj, *Microporous Mesoporous Mater.*, 2015, 203, 73–85.
- 97 Y. Li, X. Han, Y. Hou, Y. Guo, Y. Liu, N. Xiang, Y. Cui and Z. Huang, *Chin. J. Catal.*, 2017, **38**, 1831–1841.
- 98 Y. Yue, H. Liu, P. Yuan, C. Yu and X. Bao, *Sci. Rep.*, 2015, 5, 9270–9279.
- 99 M. Milanesio, G. Croce, D. Viterbo, H. O. Pastore, A. J. dos Santos Mascarenhas, E. C. de Oliveira Munsignatti and L. Meda, J. Phys. Chem. A, 2008, 112, 13745.
- 100 B. Pereda-Ayo, U. D. L. Torre, M. J. Illán-Gómez, A. Bueno-López and J. R. González-Velasco, *Appl. Catal.*, B, 2014, 147, 420–428.
- 101 A. Boubnov, H. W. Carvalho, D. E. Doronkin, T. Günter, E. Gallo, A. J. Atkins, C. R. Jacob and J.-D. Grunwaldt, J. Am. Chem. Soc., 2014, 136, 13006–13015.
- 102 A. Williams, Rev. Sci. Instrum., 1983, 54, 193-197.
- 103 H. Maeda, T. Fukunaga, K. Suzuki, K. Osamura, M. Hida, H. Terauchi and N. Kamijo, *Jpn. J. Appl. Phys.*, 1988, 27, L938–L940.
- 104 P. Behrens, *Molecular Sieves Science and Technology*, 2004, vol. 4, pp. 427–466.
- 105 K. A. Lomachenko, E. Borfecchia, C. Negri, G. Berlier, C. Lamberti, P. Beato, H. Falsig and S. Bordiga, J. Am. Chem. Soc., 2016, 138, 12025–12028.
- 106 K. Ueda, J. Ohyama and A. Satsuma, *Chem. Lett.*, 2017, **46**, 1390–1392.
- 107 S. M. Maier, A. Jentys, E. Metwalli, P. Müller-Buschbaum and J. A. Lercher, *J. Phys. Chem. Lett.*, 2011, **2**, 950–955.
- 108 D. E. Doronkin, M. Casapu, T. Günter, O. Müller, R. Frahm and J.-D. Grunwaldt, *J. Phys. Chem. C*, 2014, **118**, 10204– 10212.
- 109 M. Hoj, M. J. Beier, J.-D. Grunwaldt and S. r. Dahl, *Appl. Catal.*, *B*, 2009, **93**, 166–176.
- 110 Y. Xin, N. Zhang, X. Wang, Q. Li, X. Ma, Y. Qi, L. Zheng, J. A. Anderson and Z. Zhang, *Catal. Today*, 2019, **332**, 35–41.
- 111 K. A. Lomachenko, E. Borfecchia, C. Negri, G. Berlier, C. Lamberti, P. Beato, H. Falsig and S. Bordiga, *J. Am. Chem. Soc.*, 2016, **138**, 12025–12028.
- 112 F. Gao and J. Szanyi, Nat. Catal., 2018, 1, 174-175.
- 113 S. M. Maier, A. Jentys, M. Janousch and J. A. van Bekkum, *J. Phys. Chem. C*, 2012, **116**, 5846–5856.
- 114 I. A. Pankin, H. I. Hamoud, K. A. Lomachenko, S. B. Rasmussen, A. Martini, P. Bazin, V. Valtchev, M. Daturi, C. Lamberti and S. Bordiga, *Catal. Sci. Technol.*, 2021, 11, 846–860.
- 115 Y. Zhang, Y. Peng, K. Li, S. Liu, J. Chen, J. Li, F. Gao and C. H. F. Peden, *ACS Catal.*, 2019, **9**, 6137–6145.
- 116 X. Wei, Q. Ke, H. Cheng, Y. Guo, Z. Yuan, S. Zhao, T. Sun and S. Wang, *Chem. Eng. J.*, 2019, **9**, 123491–123502.

- 117 R. P. Vélez, U. Bentrup, W. Grünert and A. Brückner, *Top. Catal.*, 2017, **60**, 1641–1652.
- 118 A. Martini, E. Borfecchia, K. A. Lomachenko, I. A. Pankin,C. Negri, G. Berlier, P. Beato, H. Falsig, S. Bordiga andC. Lamberti, *Chem. Sci.*, 2017, 8, 6836–6851.
- 119 D. Sun, Q. Liu, Z. Liu, G. Gui and Z. Huang, *Catal. Today*, 2009, **132**, 122–126.
- 120 H. Zhu, J. H. Kwak, C. H. F. Peden and J. Szanyi, *Catal. Today*, 2013, **205**, 16–23.
- 121 P. R. Chen and U. Simon, Catalysts, 2016, 6, 204.
- 122 I. Malpartida, E. Ivanova, M. Mihaylov, K. Hadjiivanov,
 V. Blasin-Aubé, O. Marie and M. Daturi, *Catal. Today*,
 2010, **149**, 295–303.
- 123 H.-Y. Chen, M. Kollar, Z. Wei, F. Gao, Y. Wang, J. Szanyi and C. H. F. Peden, *Catal. Today*, 2019, **320**, 61–71.
- 124 R. Zhang, J.-S. McEwen, M. Kollár, F. Gao, Y. Wang, J. Szanyi and C. H. F. Peden, *ACS Catal.*, 2014, 4, 4093–4105.
- 125 J. Szanyi, F. Gao, J. H. Kwak, M. Kollár, Y. Wang and C. H. F. Peden, *Phys. Chem. Chem. Phys.*, 2016, 18, 10473– 10485.
- 126 R. Kefirov, E. Ivanova, K. Hadjiivanov, S. Dzwigaj and M. Che, *Catal. Lett.*, 2008, **125**, 209–214.
- 127 P. Concepcion, M. Boronat, R. Millan, M. Moliner and A. Corma, *Top. Catal.*, 2017, **60**, 1653–1663.
- 128 A. Frache, M. Cadoni, C. Bisio, L. Marchese,A. J. S. Mascarenhas and H. O. Pastore, *Langmuir*, 2002,18, 6875–6880.
- 129 J. Szanyi, J. H. Kwak, H. Zhu and C. Peden, *Phys. Chem. Chem. Phys.*, 2013, **15**, 2368–2380.
- 130 M.-L. Tarot, E. E. Iojoiu, V. Lauga, D. Duprez, X. Courtois and F. Can, *Appl. Catal.*, *B*, 2019, **250**, 355–368.
- 131 F. Giordanino, P. N. R. Vennestrm, L. F. Lundegaard, F. N. Stappen, S. Mossin, P. Beato, S. Bordiga and C. Lamberti, *Dalton Trans.*, 2013, 42, 12741–12761.
- 132 C. Lamberti, S. Bordiga, M. Salvalaggio, G. Spoto,
 A. Zecchina, F. Geobaldo, G. Vlaic and M. Bellatreccia, *J. Phys. Chem. B*, 1997, **101**, 344–360.

- 133 C. Lamberti, S. Bordiga, A. Zecchina, M. Salvalaggio, F. Geobaldo and C. O. Areán, J. Chem. Soc., Faraday Trans., 1998, 94, 1519–1525.
- 134 G. Turnes Palomino, S. Bordiga, C. Lamberti, A. Zecchina and C. Otero Areán, in *Studies in Surface Science and Catalysis*, ed. R. Aiello, G. Giordano and F. Testa, Elsevier, 2002, vol. 142, pp. 199–206.
- 135 J. Dedecek, Z. Sobalik, Z. Tvaruazkova, D. Kaucky and B. Wichterlova, *J. Phys. Chem.*, 1995, 99, 16327–16337.
- 136 G. Turnes Palomino, A. Zecchina, E. Giamello, P. Fisicaro, G. Berlier, C. Lamberti and S. Bordiga, in *Studies in Surface Science and Catalysis*, ed. A. Corma, F. V. Melo, S. Mendioroz and J. L. G. Fierro, Elsevier, 2000, vol. 130, pp. 2915–2920.
- 137 C. Lamberti, E. Groppo, G. Spoto, S. Bordiga and A. Zecchina, in *Advances in Catalysis*, ed. B. C. Gates and H. Knözinger, Academic Press, 2007, vol. 51, pp. 1–74.
- 138 M. Lemishka, J. Dedecek, K. Mlekodaj, Z. Sobalik, S. Sklenak and E. Tabor, *Pure Appl. Chem.*, 2019, 91, 1721–1732.
- 139 J. Grzybek, B. Gil, W. J. Roth, M. Skoczek, A. Kowalczyk and L. Chmielarz, *Spectrochim. Acta, Part A*, 2018, **196**, 281–288.
- 140 G. Lancaster, J. Mater. Sci., 1967, 2, 489-495.
- 141 H. Liu, J. Wang, T. Yu, S. Fan and M. Shen, *Catal. Sci. Technol.*, 2014, 4, 1350–1356.
- 142 M. Hoj, M. J. Beier, J. D. Grunwaldt and S. R. Dahl, *Appl. Catal.*, *B*, 2009, **93**, 166–176.
- 143 G. Principi, Metal, 2020, 10, 992.
- 144 H.-Y. Chen and W. M. H. Sachtler, *Catal. Today*, 1998, 42, 73–83.
- 145 A. R. Overweg, M. W. J. Crajé, A. M. van der Kraan, I. W. C. E. Arends, A. Ribera and R. A. Sheldon, *J. Catal.*, 2004, 223, 262–270.
- 146 Y. Li, J. Deng, W. Song, J. Liu, Z. Zhao, M. Gao, Y. Wei and L. Zhao, *J. Phys. Chem. C*, 2016, **120**, 14669–14680.
- 147 Y. Mao, Z. Y. Wang, H. F. Wang and P. Hu, *ACS Catal.*, 2016, 6, 7882–7891.
- 148 S. Bordiga, L. Regli, D. Cocina, C. Lamberti, M. Bjørgen and K. P. Lillerud, *J. Phys. Chem. B*, 2005, **109**, 2779–2784.